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AIR WEATHER SERVICE MANUAL

THE PRACTICAL ASPECT OF TROPICAL METEOROLOGY

Volume I

SEPTEMBER 1955

HEADQUARTERS
AIR WEATHER SERVICE
WASHINGTON, D. C.

UNITED STATES AIR FORCE

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HEADQUARTERS
AIR WEATHER SERVICE
MILITARY AIR TRANSPORT SERVICE
UNITED STATES AIR FORCE
Washington 25, D. C.
October 1955

FOREWORD

1. Purpose. To provide a practical manual of meteorology for the information and guidance of Air Weather Service personnel concerned with tropical regions.

2. Scope. This Manual is applicable to all Air Weather Service forecasting activities. Although many of the examples and diagrams are taken from tropical regions in the Pacific, the techniques used should be applicable within comparable latitudes of other tropical-oceanic regions.

3. Credits. This Manual was written by a team consisting of Dr. C. E. Palmer, Director of the Oahu Research Center of the Institute of Geophysics of the University of California at Los Angeles; Capt. C. W. Wise and Capt. L. J. Stempson of Project Top Hat of Air Weather Service; and Lt. Col. G. H. Duncan of the Air Force Cambridge Research Center. The studies of the Oahu Research Center, which were the basis for much of the material in this Manual, were sponsored by the Geophysics Research Directorate, Air Force Cambridge Research Center. This Manual was first issued in a very limited edition as Special Report No. 2 under Contract AF 19(604)-546 and distributed by the Geophysics Research Directorate as AFCRC-TM-55-460. Simultaneous with issuance of this report as AWS Manual 105-48, it is appearing also as Air Force Surveys in Geophysics No. 76. The McGraw Hill Book Co., Inc., has kindly given permission to reproduce Figures 2-25 and 2-26 from Climatology by Dr. B. Haurwitz and Dr. J. Austin, 1944, and Figures 2-18, 2-19, and 2-20 from Tropical Meteorology by Dr. H. Riehl, 1954.

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ABSTRACT

The report is in seven parts. After a short introduction the manner in which the tropical forecaster may utilize climatological information is discussed. The next section emphasizes that the approach to the evaluation of tropical data is different from that which is standard in high latitude meteorology. Then follows a long discussion of wind analysis, using streamlines and isotachs. The fifth section covers methods of analyzing cloud and weather distribution; the methods outlined here are designed specifically for use in tropical regions. The sixth section deals with problems of correlation of wind and weather patterns, of continuity and with related topics; the material is presented chiefly in the form of practical examples. Finally, the structure, genesis and movement of tropical cyclones are briefly discussed.

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AIR FORCE SURVEYS IN GEOPHYSICS

No. 76

THE PRACTICAL ASPECT OF TROPICAL METEOROLOGY

C. E. PALMER
C. W. WISE
L. J. STEMPSON
G. H. DUNCAN

SEPTEMBER 1955

ATMOSPHERIC ANALYSIS LABORATORY
GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH CENTER
BEDFORD, MASSACHUSETTS

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CONTENTS

THE PRACTICAL ASPECT OF TROPICAL METEOROLOGY

By
C. E. Palmer, C. W. Wise
L. J. Stempson, G. H. Duncan

1000. INTRODUCTION

The average meteorologist, trained and experienced in the analysis and forecasting of weather and winds in temperate or polar latitudes, has a tendency to regard tropical forecasting as a separate and distinct field. He has arrived at this conclusion, largely, from an inadequate knowledge of such strange and nebulous features of tropical analysis as "the inter-tropical front" or "easterly waves", which seem to be inapplicable in high latitudes; he has heard of the difficulty of forecasting the tracks of hurricanes and typhoons. He has often heard of special "schools" for the training of tropical forecasters. Finally, if he has had an occasion to see, or, perhaps, attempt weather analysis in tropical areas, the apparent failure of most of the standard methods and rules of his profession convinces him that this belongs to a special type of meteorology for which he was not trained.

To a certain extent, he is right. Many of the techniques which he uses in high latitude forecasting are based upon the recognition of the marked differences in temperature and humidity that exist between air-masses. In fact, to a beginner in low-latitude analysis, the tropical air-mass appears to be remarkably uniform in temperature and humidity and unchanging as a whole, with diurnal and orographic variations more predominant than synoptic changes. Consequently, the forecaster who uses only air-mass and frontal concepts in his work is at a loss to explain variations of wind, cloud and precipitation when these occur in the otherwise uniform air-mass. He must either invent new concepts applicable to these regions alone, or revert to the most basic and fundamental rules and techniques of analysis and forecasting, such as were used by the pioneer synopticians.

Since the average forecaster is unlikely to initiate radical new developments in meteorology that will stand the test of time, he is forced to adopt the latter alternative, namely, to return to the fundamentals of synoptic meteorology. What are these basic principles? First, he must review his knowledge of the relevant climatology - a subject to which he has probably paid scant attention in high latitudes. Secondly he must learn to understand the role of the large orographic and diurnal effects characteristic of low latitudes and to evaluate his data accordingly. For he cannot, in his analysis, describe the synoptic picture without removing these local and periodic effects and he cannot derive a forecast from his prognostic maps without including them. Thirdly, the closer to the equator his analysis extends, the less he can rely on the geostrophic or gradient wind relationships - the foundation of wind analysis in high latitudes. Moreover, he finds that the pressure gradients at the ground, and the contour gradients aloft, become weaker and weaker as the equator is approached. This leads to intolerable uncertainties in the standard pressure and contour analyses; for both these reasons, then, they cannot be used to represent the wind flow. To describe the wind field and to forecast

changes in it, he has to adopt some method of analyzing the wind observations separately from the pressure observations. Fourthly since the models of frontal and air mass analysis fail in the tropics, he has no blue-prints to guide him in deriving cloud and precipitation forecasts from the wind analysis. He has to describe the chief features of the cloud and precipitation field by some kind of weather distribution analysis.

Finally, after these tecnniques have been applied analytically, he must synthesize the results in such a way as to arrive at a true synoptic view of the weather situation, integrating and correlating as many features of the separately analyzed fields, both in space and time, as is humanly possible. Here, experience of the correlations between wind and weather and correct notions of continuity in space and time, count heavily.

In this survey, one method of treating these five fundamental steps in analysis is presented. We do not claim that it represents a new and radical approach to tropical problems, but it is hoped that the material presented will enable the reader to begin practical analysis and forecasting in low latitudes. The work is addressed primarily to forecasters who have a sound working knowledge of the synoptic meteorology of middle and high latitudes, who have sufficient academic training in general climatology and theoretical meteorology for the practical demands of middle latitude work and who have had some practical experience in the routine analysis and forecasting required to support present-day aircraft operations. Although here and there, particularly in the section that treats wind analysis, we have presented rather complex theoretical ideas, no mathematical equations have been introduced.

Geographically, the area or belt at the surface of the earth that is bounded by the Tropics of Cancer and Capricorn at 23° 27' North and South, respectively is called the 'Torrid Zone' or more briefly and inaccurately the 'Tropics'. We shall reserve the term, 'Torrid Zone' for this rigidly defined belt. However, the region covered by the tropical air mass, as shown by the horizontal uniformity of its representative and characteristic meteorological elements, often exceeds and sometimes falls short of the boundaries set by Capricorn and Cancer. For convenience, whenever we refer to 'the tropics' we shall mean the region lying between the high pressure belts at the surface of each hemisphere, and the troposphere and lower stratosphere above this region. The boundaries of the tropics therefore vary in space and time; they may approach within 15° latitude of the equator or recede 45° from it.

2100. THE USES OF CLIMATOLOGY

The synoptic meteorologist finds three uses for climatological knowledge. First, the statistical results set the limits within which the analysis and prediction of individual elements, such as wind, temperature or pressure, must fall, and the most probable value of the element for the season. For this purpose, the most valuable statistic is the frequency distribution of the element, the class intervals being chosen with a practical forecast in mind. Tropical statistics of this type, gathered over a period of many years, are practically non-existent. The surface wind roses for each five-degree square of the tropical oceans, such as appear on the "Pilot Charts of the Oceans" are probably the nearest approach to the ideal available at present. Figure 2-1, which shows the distribution of the heights of the tops of cumulus clouds over the Marshall Islands in October-November 1952, is presented merely to illustrate the type of frequency information that is most useful. This curve is based upon excellent reconnaissance data but refers only to two months and covers a very extensive area,- a very short record that should be used, if at all, with great caution,

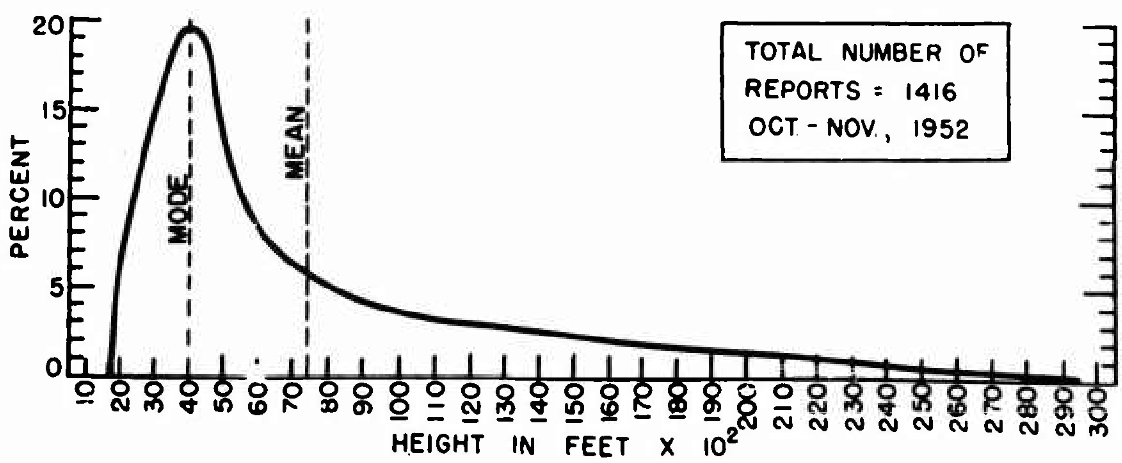


Fig. 2-1. Percentage frequencies of heights reported for cumulus tops for the area between 2.5°S - 25.0°N and 155°E - 175°W.

The modal, or most frequent height, is 4,000 feet and thus, if the curve were statistically reliable, would be the most probable height of cumulus tops in the area. In the absence of synoptic reasons against it, this is the height that should be forecast, with the greatest likelihood of success. Note the skewness of the curve; it is so great that the mean cloud height, 7,600 feet, differs by 3,600 feet from the mode. In this case the mean, therefore, is of little use to the forecaster. Note also that the curve has an abrupt cut-off at 1,800 feet, the most frequent height for the base of cumulus over the open tropical ocean. On the other hand, the curve reveals information that a high

latitude meteorologist might not suspect. Cumulus (not cumulonimbus) with tops as high as 28,000 feet can occur in the region i.e., on rare occasions the cloud tops can be super-cooled to almost -30°C (the most frequent temperature at 30,000 feet) without freezing. In the presence of good synoptic reasons for it, the forecaster need not hesitate to forecast cumulus tops between 20,000 and 25,000 feet.

Useful frequency curves for tropical weather elements are rare. For most elements and most areas the forecaster has to fall back on two less useful statistics -- the mean and the range. The range sets the limits outside of which the forecaster should not predict without very strong reasons. The mean will coincide with the mode when the element is normally distributed -- but this is rarely the case with any meteorological variable. However, in the absence of good frequency data, the forecaster may take the mean as an approximation to the mode. In practice, when one judges that after a period of unusual disturbance, the synoptic situation is about to change, the safest forecast for any meteorological element is that it will return to its mean or better, its modal value, for the month or season.

In analysis, the frequency distribution of an element, or in its absence, the range, should be used to check suspect observations. A report of a surface temperature of 60°F at Canton Island (02°49'S., 171°43'W.) would be very suspect since the mean temperature range (the mean high temperature minus the mean low temperature) at this station is 9°F and the absolute minimum is 70°F.

The second use to which statistical information may be put is in the field of correlation. The principle used is this: if one or more elements can be observed and predicted with greater accuracy than certain other elements, multiple correlations (usually suggested by synoptic theory or experience) may sometimes be worked out between combinations of the two sets of elements. When this has been done, the most probable future values of one or more of the variables which are difficult to predict can be read mechanically from a graph, which is entered at the predicted value of a more easily forecast variable. In practice, attempts are made to correlate observed values of a given element with latter values of the same or other elements. These techniques belong in the field of so-called objective* forecasting. We feel that some important research can be done in this field of tropical objective forecasting. To date, beyond some long-range monsoon forecasting in India, no work of this type has been done and no results are available for reporting here. However, the tropical forecaster might well be advised to experiment with the techniques, particularly in relation to the 24-hour forecast.

The third use for climatological knowledge is applicable to regions for which there is adequate statistical but very inadequate synoptic data. Over much of the tropical ocean the long period over which ship observations have accumulated provide reasonably good statistical information, but at any one synoptic hour very few ships report from certain areas. The forecaster may have to give an opinion on weather conditions in such areas. The best he can do under the circumstances will be to translate the statistical information. Fortunately in many parts of the tropics and for certain elements, this method

* This method is no more objective than any other in standard use -- the subjective merely enters in a different way.

will be surprisingly successful. Suppose, for example, that a mishap occurred to an aircraft flying between Hawaii and the coast of Peru, so that air-sea rescue had to be attempted at about 8°S, 110°W. It is extremely unlikely that any observations within 1,000 miles of this point would be available to a forecaster in Hawaii. Nevertheless he could use climatological maps to estimate the surface conditions in the area with some confidence. (See Figures 2-2, and 2-3.).

In summary, the tropical forecaster should make a serious study of the climatology of his area of operation. He should not only collect all the statistical information he can on entering a new region but continue to accumulate it during his tour of duty. He should experiment with new ways of using the data in forecasting and analysis -- a field in which great ingenuity can be exercised. To this end, he should possess a loose-leaf note book in which these and other data can be accumulated and in which technical experiments can be accumulated and in which technical experiments can be planned and executed. The value of the synoptician's note-book may be dramatically revealed during an emergency.

Since this is not a text-book of climatology, no attempt will be made here to provide the detailed statistical information that should go into such a note book. Since the techniques of tropical analysis that will be new to the high-latitude forecaster are those applied to the wind field (Section 4000) and the Field of Composition (Section 5000) some very brief review material on the climatology of winds (Section 2200) and Weather (Section 2300) are included here. The synoptician who is already thoroughly familiar with the general climatology of these fields may pass immediately to the analytic part of the work (Section 3000).

2200. CLIMATOLOGY OF THE FIELD OF MOTION.

Ideally, the field of motion consists of the distribution in space of the velocities of air parcels with respect to the earth. It is thus a vector field. Up to the present time, climatological data are insufficient to represent the mean field of motion completely. The past and present methods of measuring the wind direction and wind speed provide only crude approximations to the horizontal component of the velocity of the air parcels. Since no statistics are available on the vertical motion of these parcels, the climatology of the field of motion can deal only with averages of the horizontal wind. Further, the bulk of the available statistics in the tropics refer to winds measured at the surface of the earth. In the past few years, upper level wind data have increased in volume but they are now barely sufficient to provide a very rudimentary picture of the mean motion aloft.

2210. The Field of Motion at the Surface of the Earth.

Most of the climatological surface wind information that appears in the following charts is derived from the oceanic regions of the tropics. Local topography exercises a strong influence on the surface wind at any land station and large-scale topographic effects on the mean winds are evident in India, Australia, Africa and Central and South America.

<u>2211. The Streamlines of the Mean Surface Wind over the Oceans.</u> The surface wind distribution in the tropics may be studied on Figure 2-2 which shows the streamlines of the mean surface wind for the months of July and January. Here, disregarding seasonal variation, we find:

A "<u>subtropical anticyclonic belt</u>" oscillating between 20 and 40 degrees North, and another such belt between 20 and 40 degrees South. These belts

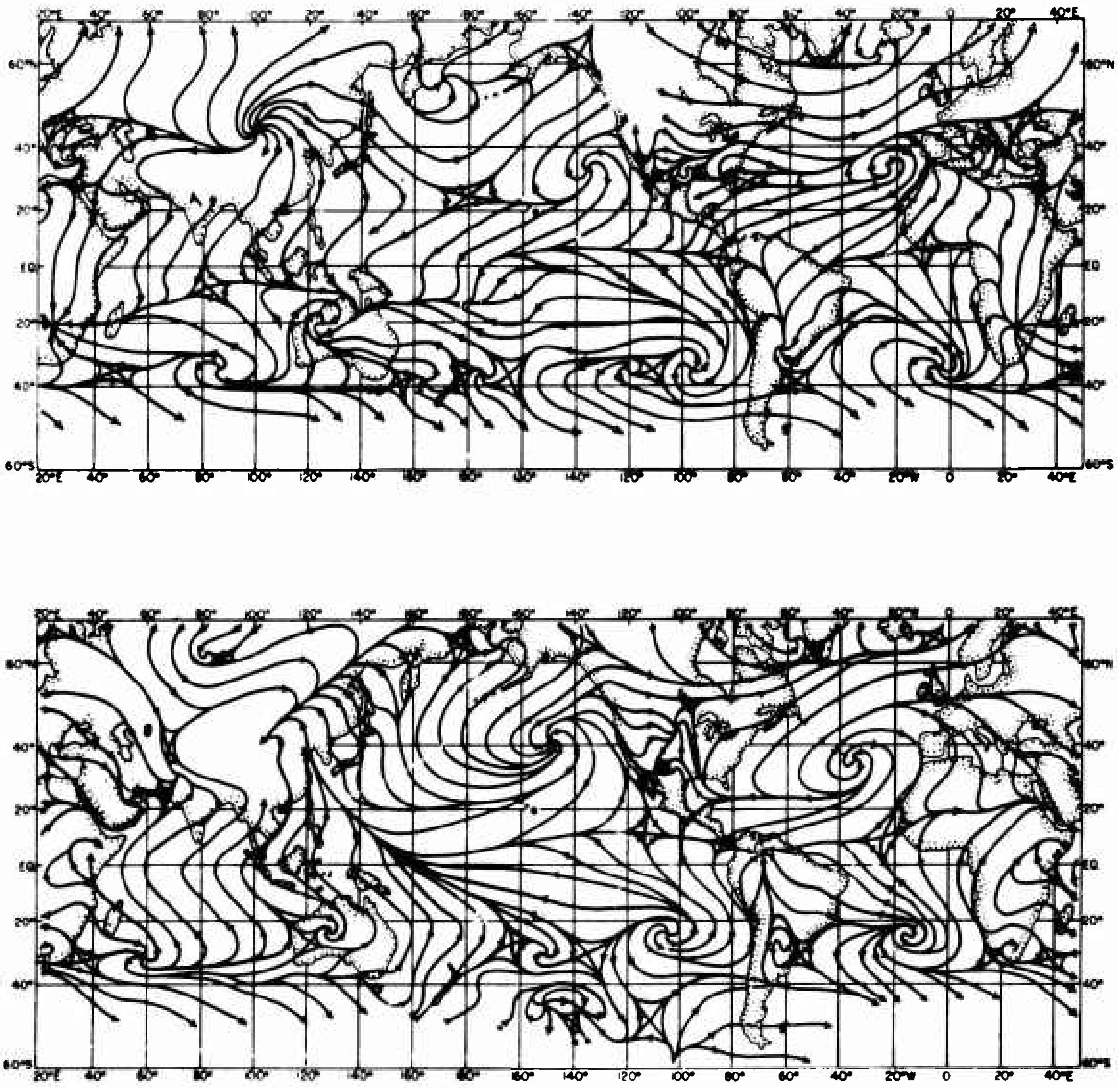


Fig. 2-2. Streamlines of the Mean Surface Wind, January (above) and July (below)

can be defined by imaginary lines connecting the anticyclonic centers which are evident in the eastern parts of the sub-tropical oceans. The centers occur at the surface in all oceans except the North Indian Ocean; in this region the centers are to be found in the middle and upper troposphere.

The "trade wind belt", or simply the "trades", located equatorward from the anticyclonic belts, approximately between 10 to 20 degrees North and 10 to 20 degrees South. The direction of the trades is normally from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. The streamlines which emanate from the subtropics appear to diverge widely as they travel toward the equator. This is especially true in the Southern Hemisphere in January, where they appear to curve clockwise over the eastern parts of the oceans.

The "equatorial trough", which, although identified primarily by the mean pressure pattern, is indicated on the wind map by the line of convergence in the streamlines in the vicinity of the equator. In the northern winter its position is clearcut, but in the northern summer, it becomes more diffuse over the large land masses being easily located only over Africa and India.

The regions in which the climatological terms described above are roughly applicable, neglecting seasonal variations, are illustrated in Figure 2-3.

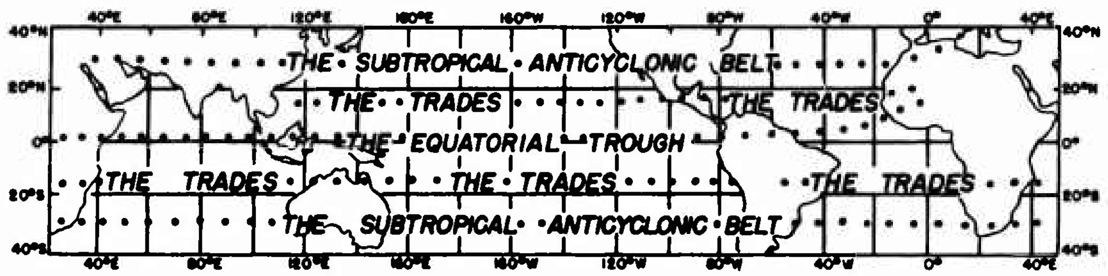


Fig. 2-3. Wind Regimes in the Tropics.

2212. The Monsoons. The only large deviations from the wind patterns outlined in Figure 2-3 stem from the topography of the continents with which they are associated. Here we refer primarily to the monsoons over India, China, Africa, Australia, and parts of the Americas. References will be made to monsoons in this work, but they will not be treated in any great detail because of their regional nature. It is considered advisable, however, to acquaint the reader with what we mean by the word "monsoon". In climatology, the word monsoon always refers to a seasonal wind blowing from continental interiors to the ocean in winter, and oppositely in summer. The monsoons are most pronounced over India, where they blow from the northeast in January and from the southwest in July. In India, the word has also come to mean the rainy season occuring from June to September. Before becoming actively engaged in monsoon forecasting, the synoptician should familiarize himself with the latest local climatological information.

2213. The Isotachs of the Mean Surface Wind. The isotachs associated with the mean streamlines (Figure 2-4) illustrate the fact that the maxima of the mean surface winds in the tropics are found in the trades and monsoons, while the minima are found along the subtropical anticyclonic belts and in the equatorial trough.

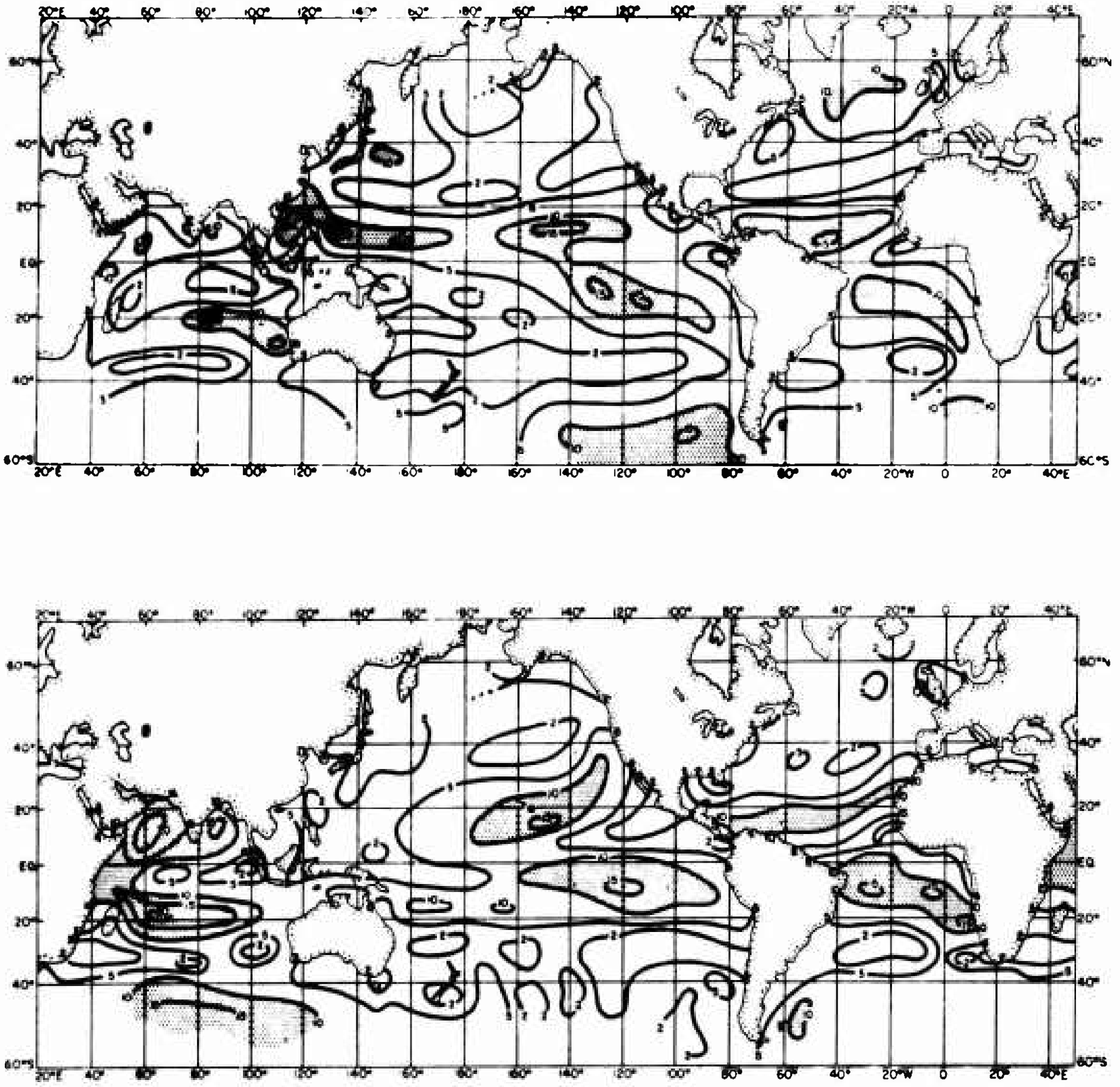


Fig. 2-4. Isotachs of the mean surface wind in January (above) and July (below).

<u>2214. Constancy of Surface Wind Patterns.</u> Conclusions of practical importance may be drawn from a study of the variability of the surface wind patterns in the tropics. Of primary interest is the fact that the surface wind patterns in some areas are quite persistent. The disadvantages of a sparse network of reporting stations are partly overcome by the use of such information. The trade winds and, in some parts of the ocean, equatorial winds, may not change direction by more than 20 or 30 degrees for periods of several weeks. This constancy of wind direction is an important forecasting tool and should be used as such whenever, and wherever, possible. To give quantitative expression to this information, Figure 2-5 is a plot of the constancy of the surface wind direction. This is given in terms of the percentage of frequency with which the wind is within 45 degrees of its modal direction. In the shaded areas the

2214.

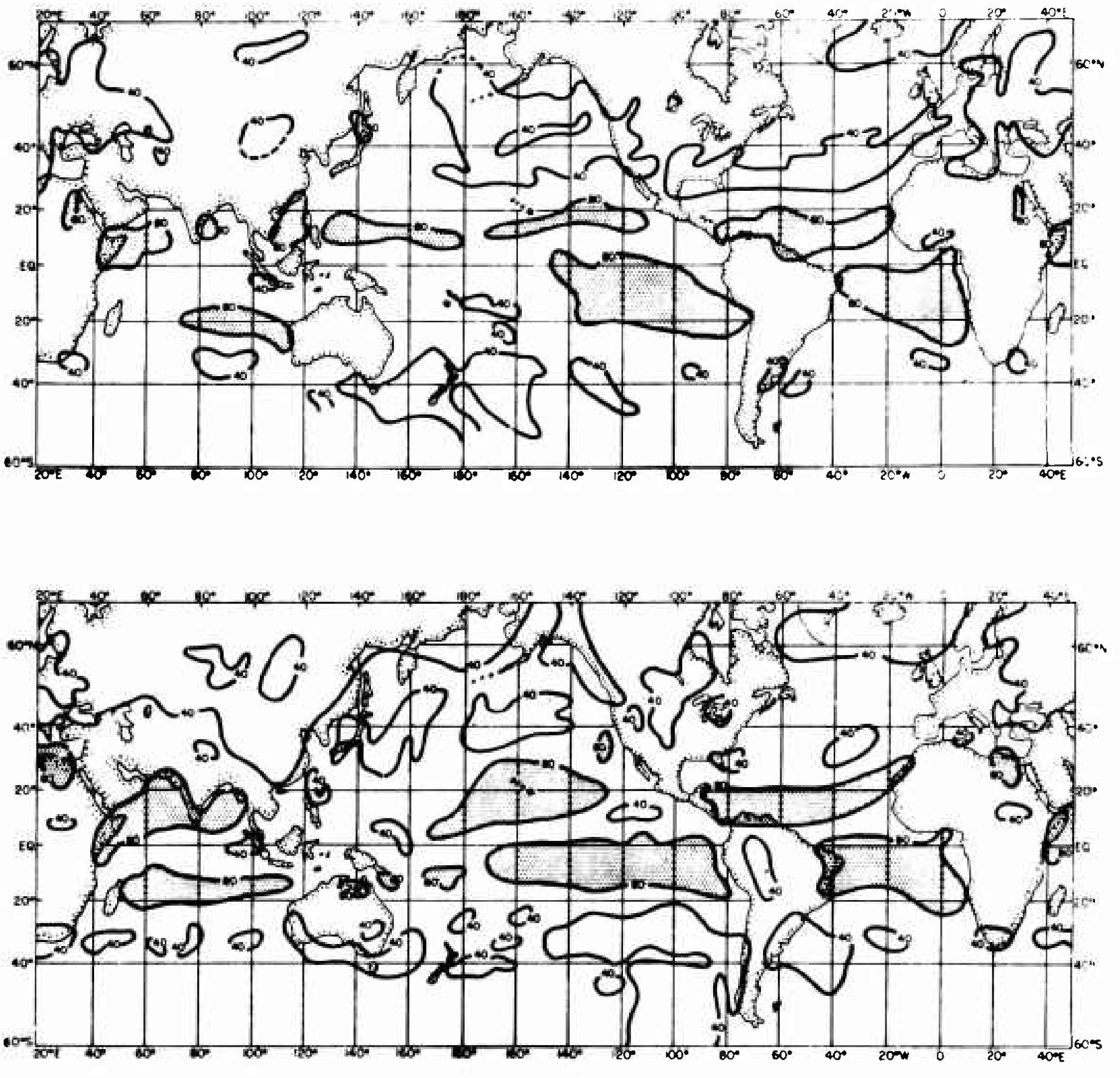


Fig. 2-5. Constancy of the surface wind direction, January (above) and July (below). The isolines show the percentage frequency with which the wind is within 45° of its modal direction.

wind comes from this 90 degree sector of the compass more than 80 percent of the time.

The greatest constancy of wind direction is found within large sections of the northeasterly and southeasterly trade area of the tropical oceans, and the southwesterly and northeasterly monsoon area of the north Indian Ocean. The least constant winds are found near the centers of the mean anticyclones, and along the line of mean intertropical convergence. It must not be inferred from Figure 2-5 that rapid changes of the wind patterns with time cannot, or do not, take place even in the trade area. The hurricane or typhoon is an excellent example of the rapid changes in surface wind patterns which may

hardly affect the climatological statistics. Further, there are often orograph-i or local effects, or minor synoptic perturbations in the wind field, which temporarily affect the persistence of the wind patterns. In light of the statistics for the entire tropics however, these conditions may be considered the exception rather than the rule and to be largely confined to the regions of low constancy shown in Figure 2-5.

2220. The Field of Motion Aloft.

The long period of observation of surface winds at sea and the high values of the constancy revealed by the tropical statistics make the mean maps of surface wind a valuable aid to the forecaster. Unfortunately the same statement cannot be made about statistical tables or mean maps purporting to show the horizontal air flow above 5,000 feet. A combination of circumstances, some of which are peculiar to the tropics, make any statistical statement on equatorial and sub-equatorial upper winds hazardous. These circumstances are:

> Radiosonde observations, leading to the construction of upper level contour maps, are of little use in delineating the wind field. The gradient wind relationship cannot be used, so that upper level maps must be based on wind observations alone.
>
> Rawin observing techniques are of very recent development, and even now are rarely used in the tropics. Thus, the very little data we have in the tropics are mainly derived from the observation of pilot balloons and cloud drift.
>
> Pilot balloons are less useful in the tropics than they are elsewhere. The predominant cloud is cumuliform, and, roughly speaking, the cloud pillars are taller in the tropics than elsewhere. Even with the sky less than half covered, pilot balloons are lost by obscuration, in most cases before they reach five thousand feet. The statistics for the levels above five thousand feet, therefore, reflect the conditions obtaining during the comparatively rare periods when there is very little low cloud of small vertical extent. They are thus highly selective, probably more so than high latitude balloon observations. Pilot balloons are also selective in another way. Since the balloon must be followed visually, its slant range from the observation point, even in clear weather is a determining factor in the heights explored. Tropical rawins have shown that sometimes the lower easterlies at oceanic stations change to upper westerlies in the middle troposphere, with a return to easterlies again at some higher level -- sometimes in other weather situations, the easterlies may remain almost constant in direction up to or beyond the tropopause. In the long run the pilot balloons will select the former situation giving a false picture of the mean circulation aloft.

On the other hand, observation of the cloud drift will tend to select "bad weather" situations, more particularly in respect of the middle clouds. In this connection we may quote from Mintz and Dean (1951): "A striking example of this condition is shown by the observations of the winter season over India, as summarized in Figure 33 (reproduced here as Figure 2-6). In this figure are shown, on the left, the streamlines of the mean vector wind, computed from pilot balloon observations at 2, 4, and 8 kilometers elevation. These streamlines show peninsular India to be beneath the <u>eastern</u> end of a middle troposphere anticyclone. But on the right in the figure are shown the

streamlines of the mean of the cloud drift directions for roughly the same heights. These cloud drift streamlines show peninsular India to the underneath the western end of a middle troposphere anticyclone. It is obvious that the clear weather days, which permitted pilot balloon observations, occurred in the mean with a different pattern of upper level circulation than the cloudy days".

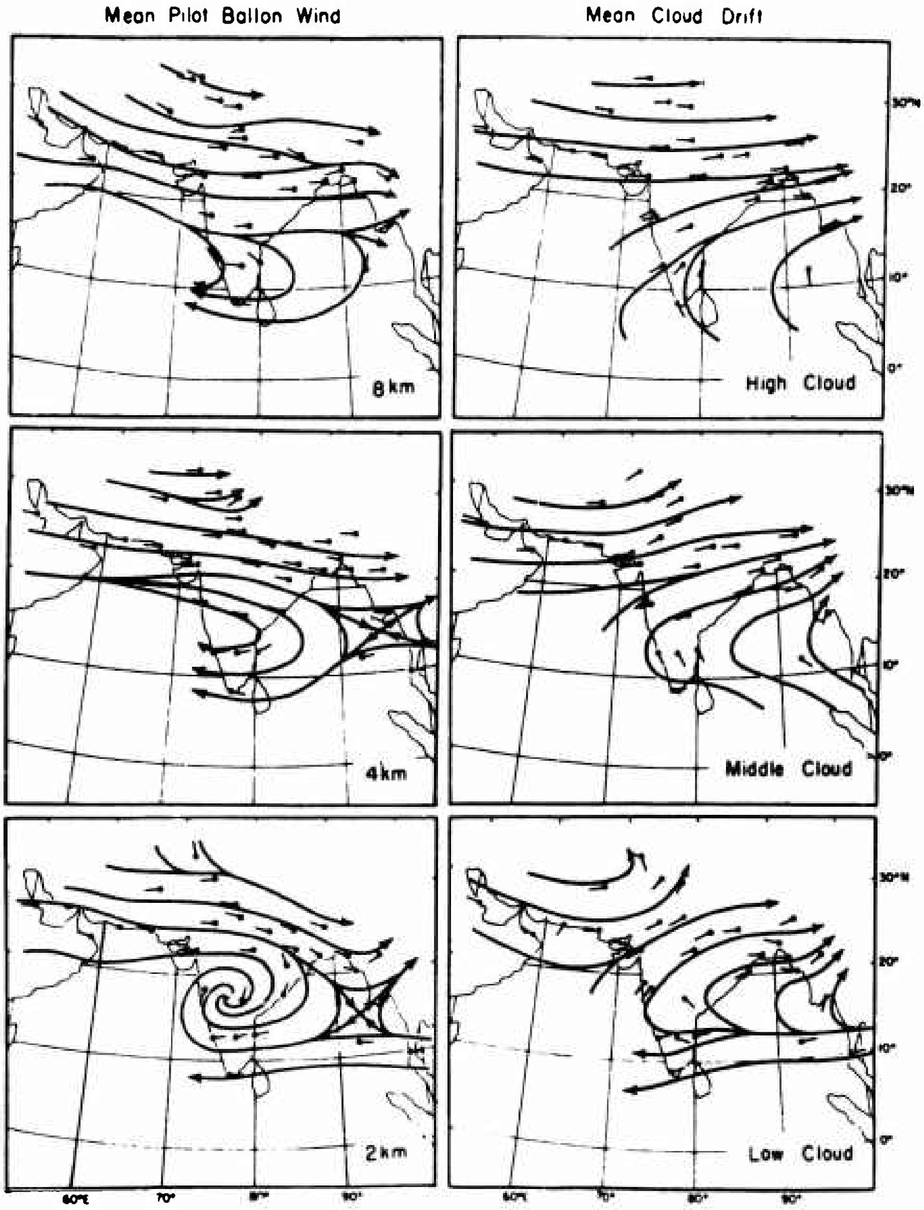


Fig. 2-6. Comparison of the direction of the mean pilot balloon wind and the mean of the cloud drift directions over India in January.

Since the only reason for introducing climatological material at all in this work is to assist the synoptic meteorologist in preparing analyses and forecasts for tropical regions, we may sum up by saying that, however interest-

ing rudimentary maps of mean flow between 15°N and 15°S may be to the theorist, the majority of those published must be treated with great caution; they are based either on pilot balloon observations and cloud drift or on "intelligent guesses" derived from theoretical notions of what the circulation might be. The only valid climatological information on the tropical upper air motions is that derived from instruments using radar techniques and then only under conditions where the slant-range selectivity, due to the so-called jet stream aloft, can be shown not to operate. In general this means that the information is restricted to the belt between 15°N and 15°S and to very narrow longitudinal zones in that belt. Poleward of the belt, statistics based on inference from the upper contour patterns are probably as reliable, if not more reliable, than those based on pilot balloon observations -- at least they are independent of cloud cover.

In view of these difficulties it is not easy to make any generalizations about the upper level mean circulation that will unequivocally guide the tropical forecaster. The following statements, however, are, in the opinion of the authors likely to be confirmed when detailed rawin information for tropical regions accumulates over a sufficiently long period:

> The tropical air flow above the surface is predominantly zonal, that is, either westerly or easterly. In general the meridional component of the winds is about one-tenth the zonal component and in many situations is much less than this.
>
> The meridional, that is the north-south, components tend to be distributed in a wave-like pattern, even more so than at the surface. This means that the subtropical anticyclonic belt aloft is split, like that at the surface, into individual "cells"by the alternating wave-like distribution of the meridional components. While this fact is easily recognized, it is more difficult to say what the mean location of the centers of these cells might be, especially in the Southern Hemisphere and especially in the high troposphere.
>
> The mountain chains exert their influence on the zonal flows to great heights. The available evidence suggests that barriers such as the Andes or the Himalayas distort the flow at heights well above their summits. "Orographic" effects, then, may be expected at all tropospheric levels, perhaps even in the stratosphere, provided the barriers are large enough. The general effect of these barriers is to increase the meridional oscillations of the wind downstream, the "trough" with the largest amplitude usually lying immediately in the lee of the barrier.

Since apart from large-scale orographic effects, the predominant directions of the upper air currents are zonal there is some profit to the forecaster in discussing an idealized north-south section through the tropical atmosphere, showing the distribution; of the east-west component with height and latitude. Figure 2-7 is such a section. It has been constructed upon information derived from many sources. Between 15°N and 15°S the greatest weight has been given to recent rawin information, though of course, the older pilot balloon and cloud drift observations have also been taken into account. Outside this belt, the chief source of data has been modern rawin observations supplemented by the fairly long radiosonde record, which through analysis of the mean contour fields, can provide a mean geostrophic zonal wind that is independent of cloud cover. It must be emphasized that this section is idealized in the sense that it represents a mean taken from data

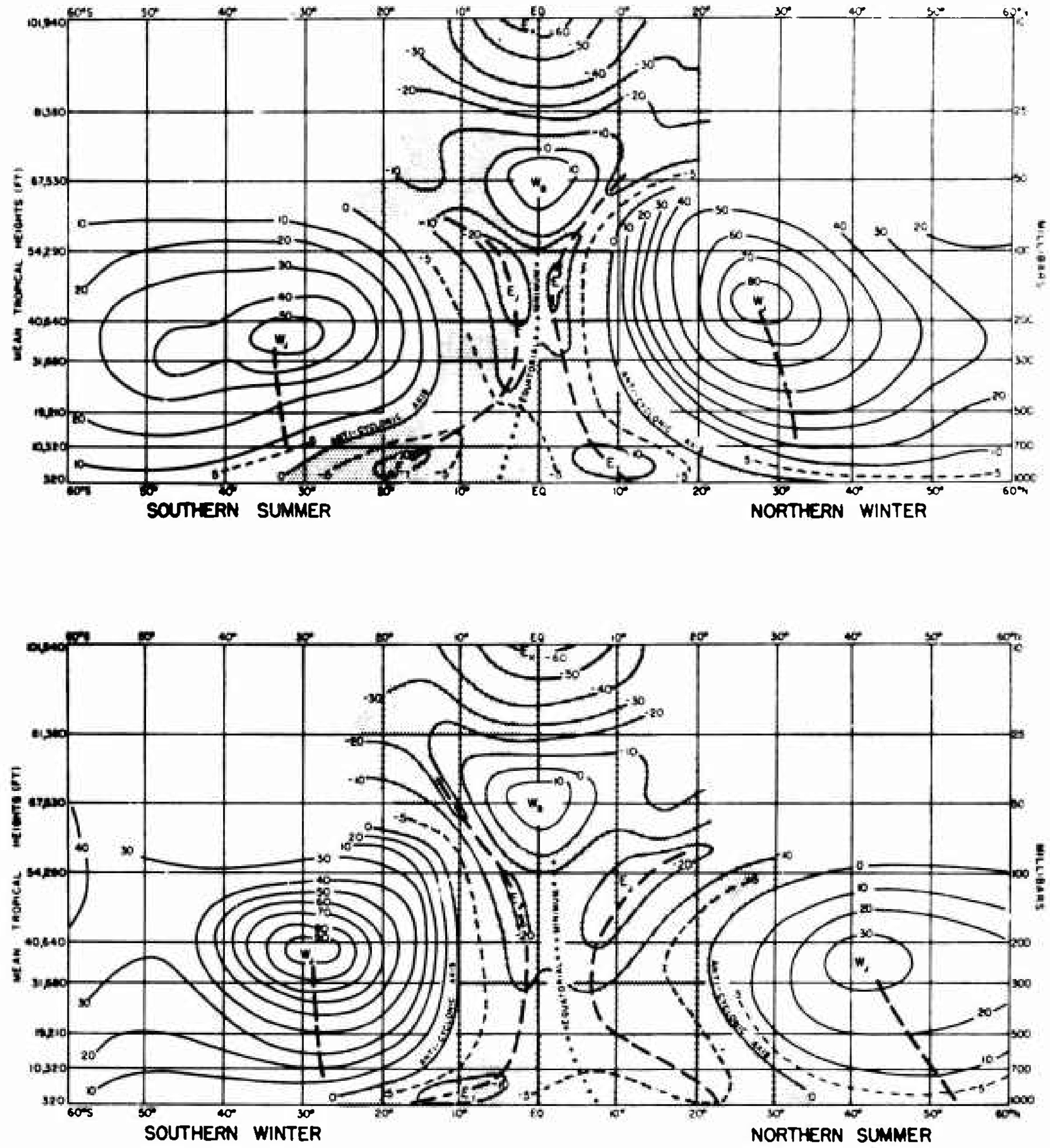


Fig. 2-7. The zonal circulation in the tropics for the winter and summer seasons.

at all available longitudes; hence the zonal wind on any given longitude will differ from the picture displayed on the figure. These variations from the mean will be discussed in greater detail below. For the time being it can be said that of all possible oceanic sections, those taken along longitudes near the central Pacific Ocean will resemble this picture most closely, those through the middle Atlantic less closely, those through the central Indian Ocean least closely. Of the continental sections, that through Africa probably resembles the ideal fairly closely, though very little is known of the tropospheric levels above 20,000 feet. The section through the Western Hemisphere

probably differs from the ideal south of the equator, owing to the presence of the Andes. The least likely to resemble the ideal will be that partial section lying north of the equator and running through India. The departure from the ideal however, will be not so much in the presence or absence of the main maxima and minima on Figure 2-7 but in their position and intensity, and in the magnitude and direction of the meridional components that accompany them. Since the maxima, minima and turning points to be described are so frequently found, not only on mean cross-sections along different longitudes but also on synoptic cross-sections referring to a given observational hour, it is convenient to name these features. The names here assigned will be frequently used throughout the text; the reader should therefore become familiar with them. At the same time we should like to insist on the point that the names have been assigned purely for convenience -- no dynamical theories are implied by them and the features themselves are only convenient descriptive landmarks in the complex atmospheric patterns, not active agents causing changes in the general circulation in some magical way.

In applying Figure 2-7 and similar sections in his daily work, the tropical meteorologist should remember that the height scale is grossly exaggerated and that this can have important practical effects. For example, on most sections the "jet stream" maximum has an exaggerated vertical extent. In forecasting upper winds the synoptician must remember that the position of the maximum has to be specified within 2,000 feet.

The tropical tropopause is remarkably constant in height both in space and time, lying close to 55,000 feet over huge areas. It is invariably marked by a strong, easily recognized temperature inversion. Consequently the zonal patterns on Figure 2-7 are conveniently separated into lower tropospheric and upper stratospheric portions.

2230. The Tropospheric Zonal Circulation. The chief characteristic of the tropospheric zonal circulation in the tropics is its relatively large seasonal variation, shown by the two parts of Figure 2-7. The seasonal variation is more marked in the Northern than in the Southern Hemisphere - note also that at corresponding seasons there is still a difference in intensity between the Northern and Southern Hemisphere's zonal flows. These general features are undoubtedly due to the difference in distribution of land and sea between the hemispheres and, probably, to the varying positions and elevations of the main mountain masses. The manner in which these differences in topography and surface heating are finally realized in the general circulation, however, is not known; this difficult subject properly belongs to dynamic meteorology and such results as have been achieved in that science to date are not yet applicable to this portion of synoptic meteorology. The observed seasonal and hemispheric variations of the zonal flows must therefore be accepted by the forecaster, without detailed explanation as the background against which he delineates the day to day changes which he studies. No matter what part of the tropics becomes his sphere of operation, he will have to take into account the following landmarks of the zonal flow pattern.

2231. The Westerly Jet (W_J). This is usually regarded as a high latitude feature and is often called the "jet stream". Notice however, that in the mean, this west-wind maximum lies almost vertically above the place where the zero isopleth (which marks the anticyclonic axis) cuts the ground. Hence the equatorward half of the jet stream system lies within the tropics (as defined in Section 1000). It is, in fact, convenient to treat the vertical boundary of the tropics

as passing through the anticyclonic axis at the ground and through the center of the westerly jet aloft. The hemispheric, seasonal and daily variations in the position and intensity of the westerly jet are sufficiently well known to the high latitude forecaster so that this knowledge may be assumed throughout the text. In passing, however, it should be emphasized that very large variations in the position of the Northern Hemispheric jet are found in the Asiatic sector. Sometimes, for long periods, the jet lies south of the Himalayas; similarly, it may appear to be "split" by that mountain barrier, one maximum lying north of Tibet, the other south. This splitting is probably topographic in origin, and thus is distinct from the splitting sometimes observed over the oceans, a feature probably due to some kind of traveling disturbance in the middle troposphere.

2232. The Anticyclonic Axis (A). This is a convenient isopleth to distinguish on all cross-sections or even on individual horizontal maps since it has long been discussed in the literature of tropical meteorology. It is defined as the zero isopleth separating the higher latitude westerlies (whether there be a definite jet or not) from the equatorial and the sub-equatorial easterlies. On contour maps, and on cross-sections showing the course of tropospheric isobars, this isopleth will lie very close to the ridge of maximum elevation of the contours. The isopleth also is frequently called the "base of the westerlies" and the variations in its elevation from day to day over a station should be carefully watched by the forecasters in that station for indications of impending changes in the local synoptic situation.

Note that the anticyclonic axes of the two hemispheres slope markedly with height toward the equator in the lower troposphere. They approach one another most closely in the region between 30,000 and 40,000 feet, above which height they depart again for higher latitudes. The slope toward the pole is very marked in the neighborhood of the tropopause, so that at quite high latitudes a thin layer of comparatively strong easterlies is often found just below and at the tropopause. In both hemispheres in the winter the anticyclonic axis is almost vertical between 25,000 and 50,000 feet. This tendency is most marked over East Asia and the neighboring ocean, during the prevalence of the north-east monsoon. On some occasions the axis is vertical from about 10,000 feet to 40,000 feet. Probably the same effect exists in other continental regions, particularly along east coasts, but there are not sufficient observations to verify this.

2233. The Trade-wind Maximum (E_T). This is a very important feature of the lowest layers of the tropospheric circulation over the oceans. Its reflection at the surface is apparent on figure 2-4. Owing to the effect of surface friction, however, the absolute maximum in this lower easterly branch of the circulation is situated some little distance above ground. Roughly speaking, one may expect to find the maximum lower easterlies near the 15th parallel and at 5,000 feet. Note that in the Southern Hemisphere the maximum retreats almost to 20°S. in the summer and advances close to 10°S. in winter. In the Northern Hemisphere the section would indicate that the trade maximum is practically non-existent in summer. This is attributable, however, to the inclusion of continental statistics in the mean. Over the continents, this trade maximum does not exist, being supplanted by the monsoons; over the sea, however, the trade maximum will be found. In this respect, the Southern Hemispheric isopleths are more representative of oceanic conditions.

Note that in all seasons the trades decrease in intensity between 10,000 feet and about 25,000 feet. The minimum easterly over the surface trade maximum is usually found at about 20,000 feet, close to the 500 mb surface. Between the anticyclonic axes of the two hemispheres at 500 mb, in fact, the mean wind patterns are very indefinite and the wind speeds very weak. This also is frequently found to be the case on synoptic 500 mb maps. It is extremely unfortunate for tropical meteorology that the 500 mb map has become almost standard for so-called upper air analysis. The tropical contours are so flat in this transition level and the winds so variable that forecasters have great difficulty in keeping continuity or even in drawing, on some occasions, any pattern at all. In contrast the 850 mb and surface maps are usually fairly easy to analyze and the patterns at 300 and 200 mb again become more definite. The sections illustrate that, of all tropospheric levels those at 30,000 and 40,000 feet will show, in the mean, the greatest contrasts in zonal wind speed and hence, with adequate data, will be the easiest to analyze.

2234. The Easterly Jet (E_J). This is rather an unfortunate term, since it might mislead the forecaster into supposing that very high wind speeds are frequently to be found in this east-wind maximum on all longitudes. However, the term has recently been introduced into the literature on the basis of studies of upper tropospheric winds in Africa and South-east Asia, and is probably here to stay. These "jets" must not be confused with the trade wind maxima, which are almost always separated from the jets by the transition layer near 20,000 feet as already mentioned. Further, it is highly probable that these upper easterly maxima are to be attributed to the dynamic effects of strong radiational cooling in the upper tropical troposphere, a cooling that sometimes results in temperatures as low as -91° C being recorded at the tropical tropopause; the easterlies of the trade winds cannot be explained in this way.

The easterly jet is best developed in the summer hemisphere. The sections overemphasize this variation, however, chiefly because continental statistics have been included. Over Southeast Asia and Central Africa (and to a lesser degree over Australia) very high east winds in the easterly jet region may persist for days or weeks. Speeds in excess of 60 knots are not uncommon. The only oceanic section that clearly shows the jets is that across the Central Pacific. Here the seasonal variation, and the extreme speeds reached on occasion are not nearly as great. Very little information is available from the Atlantic. The most recent statistics are those derived from the German "Meteor" expedition, 1925-1927. These statistics indicate that westerly winds are frequently found at these altitudes even on the equator. However, all the observations were made by pilot balloon and very few (by comparison with rawinsonde) reached these levels over the two year period. The selectivity of the pilot balloon undoubtedly operated to make the "Meteor" results statistically represent the common "equatorial westerly" situation to be described in the next section. On the other hand, one must conclude from the "Meteor" results that the easterly jets over the atlantic do not reach the strength of those over Central Africa and Southeast Asia.

2235. The Equatorial Minimum. (M). Despite large seasonal variations, the zonal circulation shown on Figure 2-7 has a qualitative symmetry. There are two westerly jets, two easterly jets and two trade wind maxima. Between the trade wind maxima in the lower layers, and between the easterly jets aloft

lies a region of minimum east wind which acts roughly as a quasi-vertical axis of symmetry; this separates the regions of maximum zonal flow in one hemisphere from those in the other. This region has been given many names during the past two centuries. At the surface it was first known as the "doldrums", a term still in common use but largely supplanted among synoptic meteorologists by names like "equatorial front", "intertropical front", "intertropical convergence zone", all of which imply some theory concerning the origin and maintenance of the surface wind speed minimum. These terms also have been applied to the minimum aloft, especially the names which imply that the speed minimum is a sloping frontal surface. For some time the term "meteorological equator" seemed to fulfill the requirements for a non-commital term, distinguishing the whole system both at the surface and aloft, from the geographical equator. However, the concept became confused in the minds of some meteorologists with the so-called heat equator and thus became loaded with theoretical implications. So, we are forced to use the clumsy term "equatorial minimum" or "equatorial wind speed minimum" to avoid theoretical implications, even though at high levels, in the stratosphere, the axis of symmetry is marked, not by wind speed minima, but by maxima, westerly below and easterly above.

The leading characteristic of the equatorial minimum is not so much the low wind speeds but the variability both in speed and direction of the winds in its neighborhood. This was also the leading feature of the classical description of the surface doldrums - we now find that the same properties belong to the region aloft. The statistical representation of the axis in the troposphere, shown in figure 2-7, then, is not to be regarded too seriously. On certain longitudes and in certain seasons, one may find the axis marked, not by weak easterly winds, but by moderate west winds; moreover, sometimes these west winds may be found close to the surface, being overlaid by weak easterlies aloft, or, on other longitudes, these "equatorial westerlies" may be present aloft, superimposed on weak easterlies below. It has recently been found that, in the same month and the same locality, the winds in the equatorial minimum above 20,000 feet may be, in the mean, exactly opposite in direction in two different years. Before any statement can be made about the mean wind directions aloft in this region, it will be necessary to collect rawin data extending over many years. In the meantime, the forecaster has the valuable information that, in contrast to other parts of the tropical zonal circulation, this equatorial minimum is a highly variable region, the seat of many disturbances of synoptic importance - not only at the surface, as has long been known, but also aloft, even up to the tropopause.

2240. The Stratospheric Zonal Circulation: The chief characteristic of the stratospheric zonal circulation in the tropics is its small seasonal variation. The steadiness of the wind in the two main maxima over the equator is quite astonishing, exceeding that of the surface trades for months at a time. On the other hand the heights at which these maxima are found, and their intensity, vary from year to year, suggesting long-period variations in the stratospheric circulation.

Normally, the tropical synoptician is not required to forecast changes in the stratospheric circulation. Further, much less is known about this region than about the troposphere. However, for interest, and to give a

tentative picture of the present state of research in this field the following quotation from a recent paper (Palmer 1954) on the subject is presented.

"Knowledge of the tropical stratospheric circulation begins on 27 August 1883, when the great volcanic eruption of Krakatoa (6° 9' S., 105° 22' E.) blew a cloud of fine dust through the sub-equatorial tropopause. The main body of the cloud lay initially at 32 Km. (105,000 feet, 9 mb.); by the early part of September, it had descended to 25 km. (75,000 feet, 35 mb.) and it remained near that level until late November 1883 (Pernter, 1889). Wexler's (1951) excellent summary of its history states '..... the main body of the cloud moved from east to west at an average speed of 73 miles per hour, completing at least two circuits of the earth in equatorial latitudes.' Although until very recently, extensive data suitable for statistical analysis have been lacking, most of the sporadic observations in the past 60 years that refer to the 30 km. level in sub-equatorial and equatorial regions have confirmed the existence of the 'Krakatoa winds' (a term due to Van Bemmelen 1924) as a persistent part of the general stratospheric circulation (E_K)..... this general atmospheric motion may be defined as (1) confined to the tropics, being prevalent usually between 15°N and 15°S; (2) predominantly zonal, from the east; (3) of high speed, varying about 30 m/s; (4) prevalent on all longitudes so far explored .....; and (5) prevalent from at least 30 km. to as high as the highest balloon soundings extend, which may be taken as about 40 km..... Van Bemmelen not only identified the Krakatoa winds as part of the general circulation but also described what he called the 'hoher westwind' already mentioned; this system was first observed near Central Africa in 1909 by Berson.... they will be called the Berson westerlies (W_B). Since they occur at stratospheric levels lower than those of the Krakatoa winds, much more is known about them. They constitute a narrow 'thread' of steady west winds whose axis lies at about 2°N., and whose base usually lies near 20 km.; the upper transition to the Krakatoa winds varies from month to month and year to year. Latitudinally, the westerlies rarely extend more than 7° on either side of 2°North, and often the thread is much narrower than this. They are, however, worldwide, extending, like the Krakatoa winds, as a ring around the equator. The atomic test data show their presence (Palmer 1951b; Korshover 1954 a,b); they have recently been reported from Singapore (May, 1953); their prevalence near the equator in Italian Somaliland has been suspected for some time (Bossolasco 1949). In the Pacific, it is now known that they extend at least as far as Palmyra and Canton Island (Palmer 1951b), near longitude 160°W. Information from equatorial America, unfortunately, is still lacking, but their presence over the equatorial Atlantic is suggested by one of the cross-sections Vuorela (1950)."

2250. Transition Levels of the Tropical Upper Air. Detailed climatological studies of the upper winds in the Marshall Islands are now available (Palmer 1951b, Korshover 1954 a,b). These studies were made possible by the availability of data from the recent atomic testing periods in the Pacific, and they are considered to be the most comprehensive study of this kind ever attempted in the tropics. Naturally, these studies cover only a small area, not much larger than the United States, but there are certain facts and correlations that may be drawn from them that appear to apply to the tropics generally. One of the most important of these concerns the steadiness of the upper winds. Figure 2-8 constitutes a cross-section of four stations in the Marshall Island area and illustrates the steadiness of the upper winds at Kusaie, Kwajalein, Eniwetok and Wake.

The steadiness of the wind is defined as the ratio of the speed of the resultant mean wind to the mean wind speed irrespective of direction. Thus, if the wind always blows from the same direction, the steadiness is 100%. At each station, two curves (October 1952 and February 1954) are presented. At first glance, the curves seem to have little if any similarity, excepting

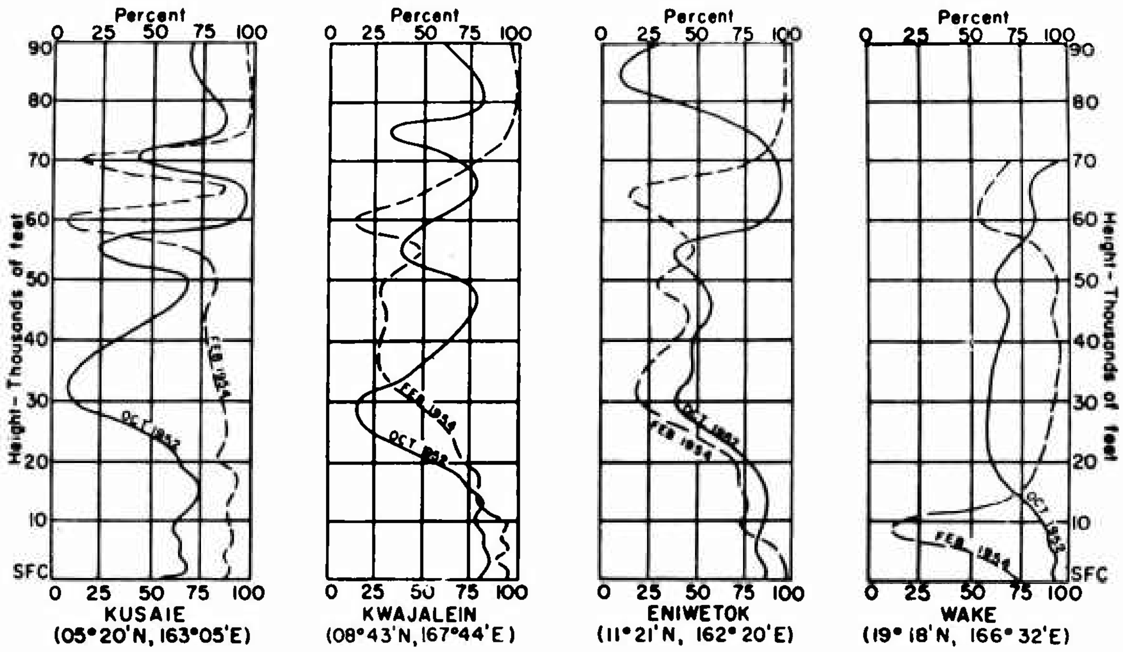


Fig. 2-8. Constancy of the upper winds near 165° E., in percent.

the curves in the troposphere at Eniwetok. Closer inspection reveals several important facts:

The 30,000 foot level at Kusaie shows 10% steadiness in October, as compared with 86% in February. This clearly illustrates the magnitude of the variation in steadiness which can occur in the middle troposphere.

The curves between 20,000 feet and 50,000 feet at Kwajalein are significant in that they indicate how the levels of steadiness, or unsteadiness, are apt to change with time.

The curves at Eniwetok are similar in the troposphere, but the most marked change in both height and percentage of steadiness in the stratosphere (between 55,000 and 90,000 feet) occurs here.

The curves at Wake are presented primarily to point out the marked changes in steadiness below 10,000 feet that can occur in a region normally occupied by the trades.

In summary, the maximum or minimum steadiness of the winds, in the central tropical Pacific at least, do not consistently lie at any particular level in the atmosphere.

2250.

The meteorologist first faced with the problem of analysis and forecasting of upper winds at one or two standard levels in the tropics is often appalled at the apparent unsteadiness of these winds. If he is accustomed to notions of continuity applicable to analysis and prognosis of winds at standard levels in middle latitudes, he can see little rhyme or reason to the changes of wind direction and speed that may suddenly occur at similar levels in the tropical upper air. The tropical forecaster now recognizes these rapid changes of wind direction and wind speed to be associated with the "shear"or "transition" level between two separate and distinct wind circulations, one overlying the other. In the tropics, these wind circulations are usually defined in their zonal sense, as easterlies or westerlies; of course, meridional components also exist. The zonal component of the wind at Kusaie, shown on the

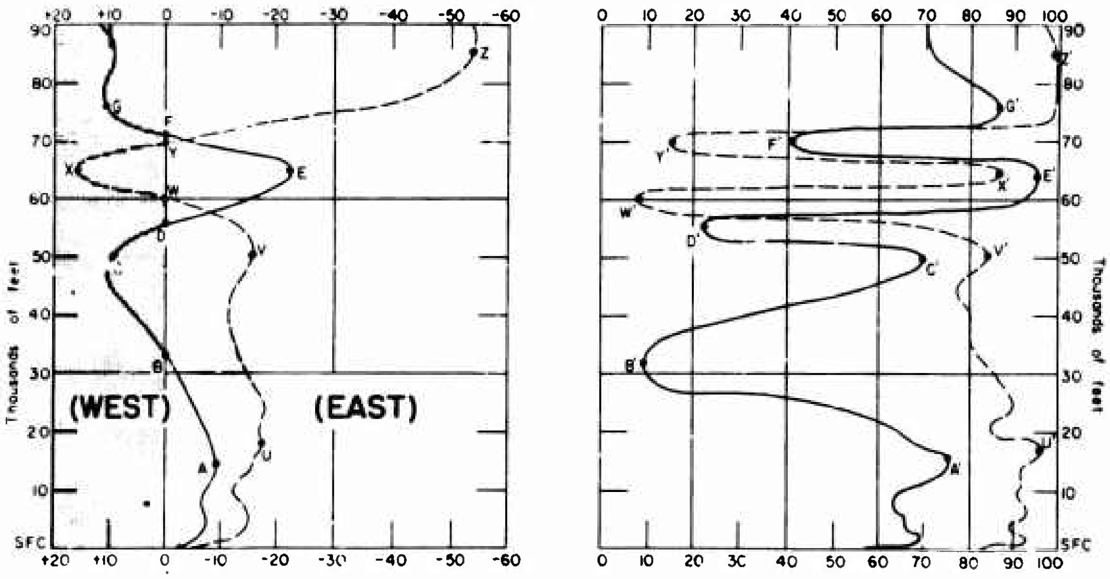


Fig. 2-9. Zonal component of the wind at Kusaie in knots, October 1952 (solid) and February 1954 (dashed), at left. Steadiness of the wind at Kusaie in per cent, October 1952 (solid), February 1954 (dashed), at right.

left of figure 2-9, illustrates these shear levels and wind circulations very distinctly. Here the zonal component of the mean wind shifts from easterly to westerly, or vice-versa, at points B, D, W, Y and F.

The wind circulations over restricted regions then have a "layer-like" appearance. Each layer will appear to have fairly strong winds blowing from a nearly uniform direction. (This direction may change with time, and the implication that winds of a given direction are always to be found at a given level is not intended). In the center, or core, of each layer, illustrated by points A, U, C, V, X, E, G and Z, we usually find the highest wind speed values. The layers can be quite persistent, often being present at varying levels over a specific area, througnout the entire year, and both these layers and the transition levels may become evident when comparing reports from air-

craft flying along a fixed route, but at levels that differ as little as 1,000 feet. When plotted together, the reports show a jumble of wind directions, but when separated according to the height of the aircraft, the winds are likely to show different, but consistent, patterns of the wind flow (see section 4620). The nearby rawins will indicate that the flight levels of the aircraft are within the zone of transition.

A final correlation may be drawn by further examining the graphs in figure 2-9. When compared, these graphs point out two very useful features:

The coincidence of high values of steadiness is found at the same levels in the atmosphere as the corresponding high values of the zonal component of the wind. This is demonstrated when comparing points A with A', U with U', C with C', V with V', X with X', and E with E'.

The coincidence of low values of steadiness is found at the same levels in the atmosphere as the corresponding low values of the zonal component of the wind. This is demonstrated when comparing points B with B', D with D', W with W', Y with Y' and F with F'.

Briefly, then, the comparative zonal wind speeds are indicative of the levels of steadiness and unsteadiness of the winds in the tropical atmosphere. Such information may be used to advantage by the forecaster in determining those levels of the atmosphere where the winds will more clearly represent the upper wind patterns.

2300. CLIMATOLOGY OF THE FIELD OF COMPOSITION

The phrase "field of composition" is adapted to replace a term from a publication by V. Bjerknes (1911) in which he used the phrase, "field of humidity". This field included all of the meteorological elements such as cloud, precipitation, visibility and dewpoint, most of which depend on the distribution of water substance and which the modern meteorologist loosely terms "weather". Since that time, the word "humidity" has acquired a more specific meaning and is no longer used in the sense that it refers to these many forms of water substance. It was for this reason that we described this field as the "field of composition". Specifically, it is meant to include all of the meteorological elements indicating the presence of water substance in any of its three states of:

Liquid, (rainfall, cloud forms and fog)
Solid, (ice crystals in various forms)
Vapor, (dewpoint, mixing ratio and relative humidity)

and the polution of the air during its movement over water surfaces (salt particles), and land surfaces (dust, smoke and other foreign particles).

In contrast to the field of motion, a great deal of information regarding the field of composition in the tropics is available to the statistician. Most of this information, which has been observed and recorded since the middle of the nineteenth century, is in the form of statistics on cloud structure and cloud cover, precipitation, visibility and dewpoint, as observed from the surface of the earth. In comparison, much less is known about the moisture distribution in the upper air. Convection in the tropics is highly cellular. Radiosonde flights through convective clouds will provide different data from those taken in the adjacent subsiding layers and neither will be representative of the mean stratification. In view of these

deficiencies, the distribution of moisture aloft, presented here, will not be considered entirely representative.

The United States Weather Bureau, in 1938, published an excellent set of climatological charts showing the seasonal cloud distribution over the oceans. These charts were based upon more than 5½ million ship observations taken over a period of 50 years, and they still constitute the most comprehensive work of this nature in existence. Many of the charts will be presented in this section in a modified form. The modification deals only with the method of presentation; the data remain the same.

Since most of the tropical atmosphere lies over water, the charts may be considered representative of the greater portion of the tropics. It is unfortunate that similar charts have not been compiled for all land areas. In some cases, statistics have been available for both land and water areas, and these have been included wherever possible.

2310. Tropical Cloud Distribution. A popular conception of the cloud distribution in the tropics pictures the equatorial regions as a tremendous factory incessantly producing cumulonimbi which, because of the height of the tropopause, rise to spectacular heights. This is true only of certain regions. All types of high, middle and low clouds are present in tropical regions; some are reported infrequently, while others, in certain localities, are often present every day of the year. The record shows that cumulonimbi are more common in the tropics than in polar regions, but it also shows that, except for such places as Central Africa, Southeast Asia and Indonesia, the Amazon Valley and the Southern United States, the cumulonimbus is the exceptional cloud, rather than the most common. In fact, certain equatorial regions are known to report few, if any, cumulonimbi throughout the year. Cumulus, in one or another of its many forms, is the predominant tropical cloud.

The climatology of the tropical clouds, like those in middle and high latitudes, may be divided into two parts; (1) climatology of clouds over the oceans and, (2) climatology of clouds over land. The orographic effect of islands upon the type and form of cloud cover is even more pronounced in the tropical oceanic regions than elsewhere. The higher mean temperatures of tropical air, with its greater capacity to hold water vapor, results in orographic cloud with even the slightest forced lifting. Another factor governing oceanic cloudiness in the tropics is the strength and height of the trade inversion. The moisture content of the air above the trade inversion decreases markedly, and the strong stability at the inversion effectively limits the vertical extent and development of the clouds. Finally, the absence of a variety of air masses of different origin eliminates the association between fronts and clouds that is so pronounced at higher latitudes and leaves us with only the basic differences between the air mass clouds over land and those over water surfaces.

2311. Mean Cloudiness. Cloudiness is measured in terms of the amount of sky covered by clouds as seen by an observer at the surface of the earth. Until recently, it has usually been represented in tenths of the total area of the sky. This must be remembered in interpreting mean values of cloudiness; thus, if a station is either completely cloudless half of the time and

completely overcast (10/10ths) the rest of the time, the mean value will be near 5/10ths, even though this value may occur infrequently, if at all. The mean cloudiness, then, cannot be used uncritically as a forecasting aid. The frequency of occurrence of each amount of sky cover is, if available, a much more valuable aid (see section 2100).

The latitudinal distribution of mean cloudiness in the tropics is shown in table 2-1. Here, it is clear that a maximum of cloudiness occurs in the immediate vicinity of the equator near the normal position of the equatorial trough, while a minimum occurs near 25° North and South, near the latitude normally occupied by the sub-tropical anticyclonic belt. The principal maximum of cloudiness occurs at higher latitudes, and this is due primarily to frontal cloud systems well beyond the normal tropical limits.

LATITUDE	50°-40°	40°-30°	30°-20°	20°-10°	10°-0°
NORTHERN HEMISPHERE					
OCEAN	66	52	49	53	53
LAND	50	40	34	40	52
MEAN	56	45	41	47	53
SOUTHERN HEMISPHERE					
OCEAN	67	57	53	49	50
LAND	58	48	38	46	56
MEAN	66	54	48	48	52

Table 2-1. Annual means of the cloudiness, in per cent. (After C.E.P. Brooks)

Maps of the distribution of cloudiness over the earth during January and July are shown in figure 2-10. These maps show the mean cloudiness for those months in tenths.

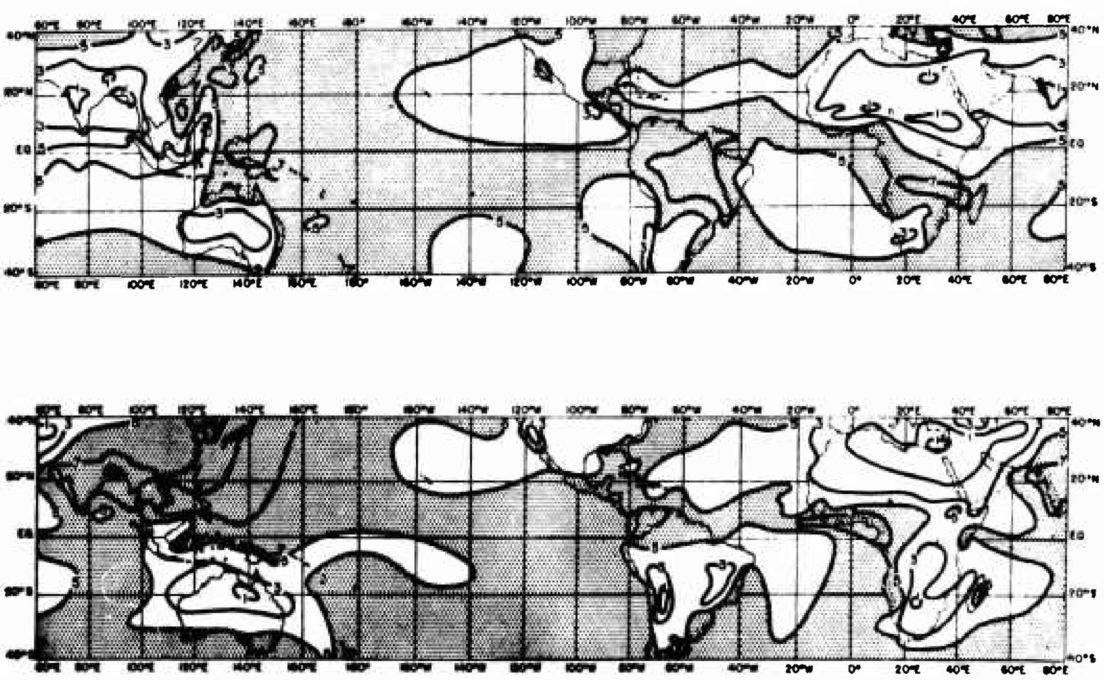


Fig. 2-10. Mean cloudiness for January (above) and July (below) in tenths.

Figure 2-10 has the following features of interest to the forecaster:

As in table 2-1, the maximum cloudiness is found along the equator, and the minimum is found along the sub-tropical anticyclonic belts.

Cloudiness on the whole is greater over the oceans than over land.

The latitudinal distribution of cloud roughly parallels that of precipitation, as shown in figure 2-17.

The seasonal variation of cloudiness can be very pronounced in areas affected by monsoons.

2312. Distribution of High (Cirriform) Clouds. Prior to the "jet age", the presence of high clouds was a matter of theoretical interest, but it presented no hazard to normal aircraft operations.

The current operating level of jet-type aircraft in the tropics has now surpassed 30,000 feet, and, since the average height of the cirriform clouds in the tropics lies roughly between 30,000 and 40,000 feet, the forecaster now has to predict their distribution. The first question is, of course, "What is the seasonal distribution of these clouds?". Figure 2-11 shows the average frequency of high cloud cover over the oceans for the winter and summer seasons, in per cent. Here, no attempt is made to separate the various

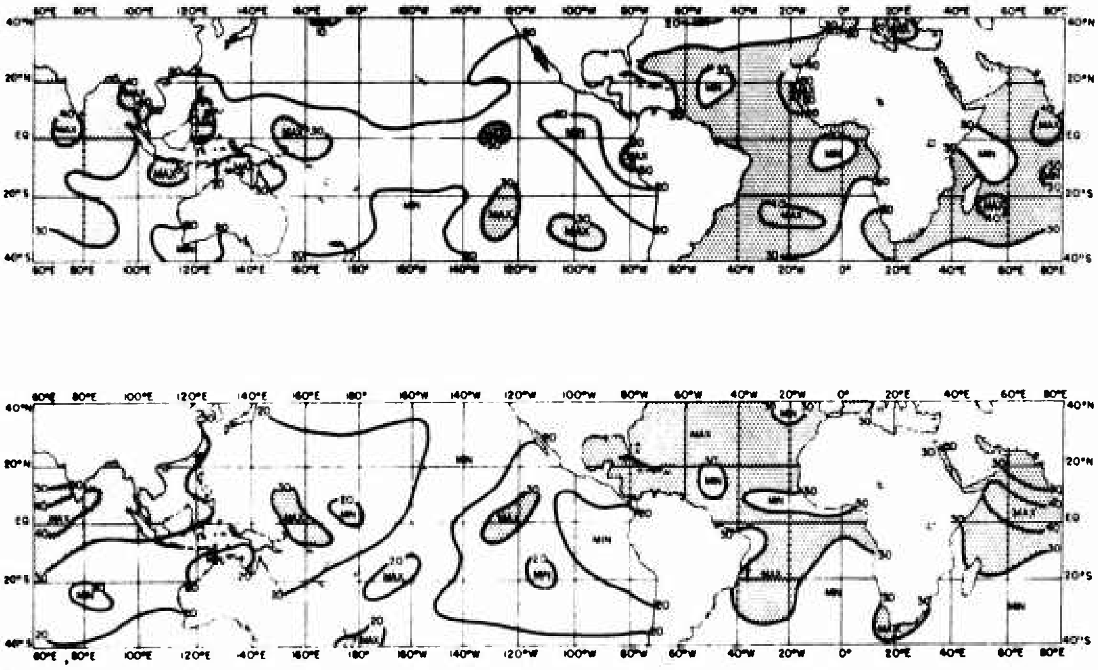


Fig. 2-11. Average frequency of high clouds (cirrus, cirrostratus and cirrocumulus) for the seasons: December, January and February (above), June, July and August (below), in percent.

forms of cirrus. Instead, they have all been grouped together and presented as a single type of cloud. Also, the values indicated in this figure are probably suspect, since the statistics were based upon observations taken at Greenwich Meridian Noon time. This means that many observations in the Pacific were taken in darkness, and certain forms of cirrus are extremely difficult to observe at night. Further, this distribution is conditioned by the amount of low cloud cover. Obviously, if the sky is covered with low clouds, even a

cirrostratus overcast would not be visible to an observer on the ground and consequently would not be reported.

Figure 2-11 indicates four climatological features:

Cirriform clouds in varying amounts are found everywhere in the oceanic tropics.

Isolated maxima of high cloudiness are found near the equator, some of which may be attributed to the prevalence of the anvil tops of cumulonimbus clouds.

Cirrus is found more frequently over the tropical Atlantic and Indian Oceans than over the tropical Pacific. This does not agree with synoptic experience; it is probably the result of compiling the statistics only from observations taken at 1200 GCT (night in the Pacific).

An overall seasonal variation of high cloudiness is not evident in the tropics. Certain localities, such as Northern Australia, the South Indian Ocean and the west coast of Africa, experience seasonal changes, but these are not large enough to be considered representative of the tropics as a whole.

2313. Distribution of Middle Clouds. All varieties of altostratus and altocumulus clouds will be classified as middle clouds in this section. Figure 2-12 will give the reader an idea of the frequency of occurrence of these clouds in the winter and summer seasons. As with the cirriform clouds, the

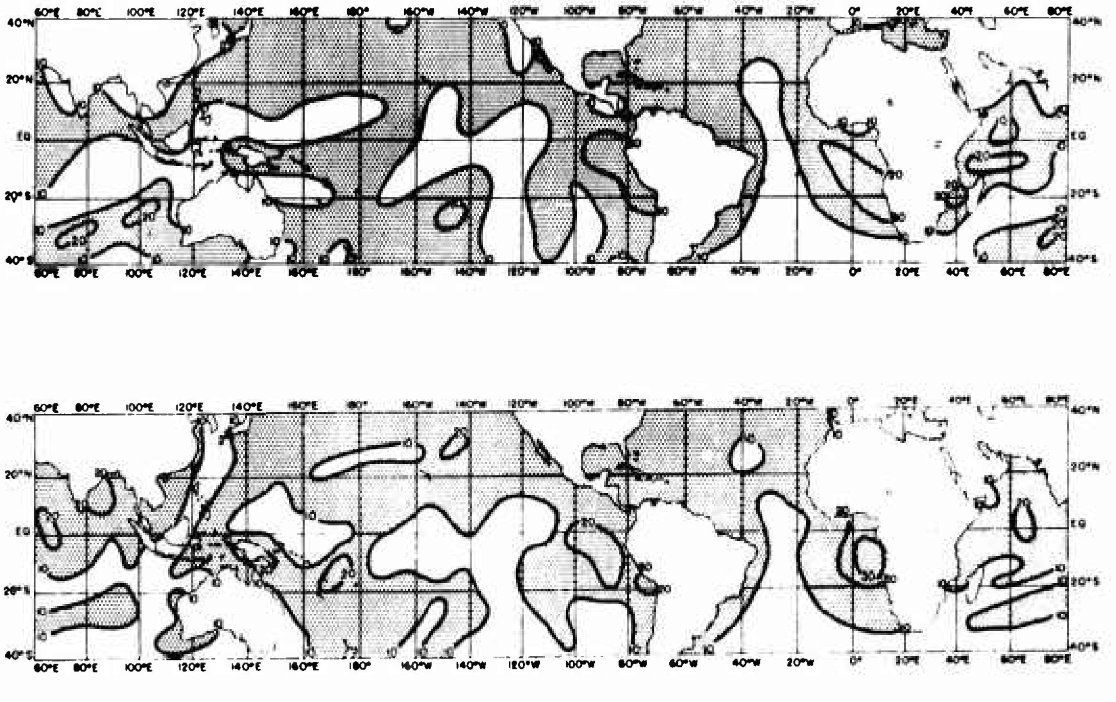


Fig. 2-12. Average frequency of middle cloud types (altostratus and altocumulus) for the seasons. December, January and February (above) and June, July and August (below), in percent.

percentage frequency with which middle clouds are reported may be somewhat low. This is due, primarily, to the inability of the observer to report

these clouds when the sky is covered with lower clouds. The main climatic features of the middle clouds are:

Middle clouds are likely to be found everywhere in the tropics and in any season of the year.

No appreciable seasonal variation occurs in the global distribution.

No pronounced minimum or maximum of middle cloudiness is evident along any particular latitude in the tropics.

A slight tendency exists for minima and maxima to occur along certain meridians in the Central Atlantic and the Eastern Pacific Oceans.

2314. Distribution of Low Clouds. The final cloud category is that of the low clouds. This includes the many forms of cumulus and stratus whose bases are usually found below 10,000 feet. Because of the marked differences in the mode of formation and the appearance of the different varieties of low clouds, they have been separated into three primary categories; (1) cumulus, (2) stratus and stratocumulus, and (3) cumulonimbus.

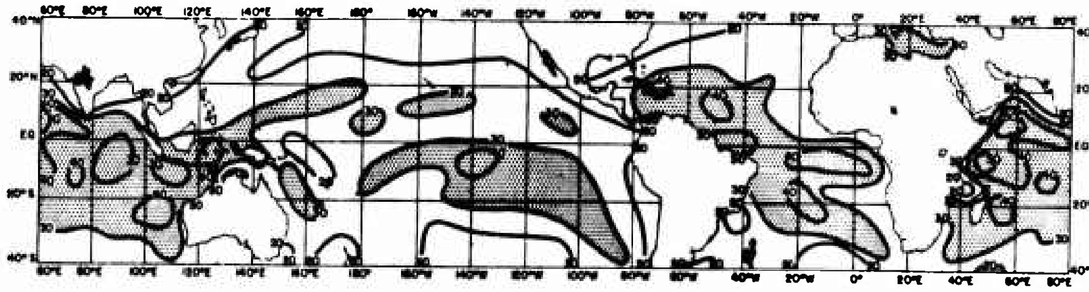
Of all forms of cloudiness, the low cloud still commands the greater portion of the forecaster's attention. In many tropical areas, an increase, decrease or change in form of low cloudiness is often an indication that the "normal" weather and cloud pattern will be disturbed. Since the most predominant clouds are the low clouds, importance is usually placed upon forecasts of their distribution, amount and thickness. The pilot, especially, is still concerned with low clouds and their attendant precipitation.

It is not uncommon for the bases of cumuli and cumulonimbi to decrease a thousand feet or more while precipitation is in progress. Even in oceanic regions in the tropics, ceilings during precipitation are often reported below one thousand feet MSL. This lowering of cloud base, when combined with the usual poor visibility in moderate or heavy precipitation, still presents a definite hazard to the pilot making visual approaches and landings.

The average frequency of the occurrence of cumulus clouds over the tropical oceans for the winter and summer seasons is presented on the next page in figure 2-13. The reader is cautioned to remember that the data presented in figure 2-13 do not include the distribution of cumulonimbi. A separate figure, (Figure 2-14) shows the frequency of occurrence of cumulonimbi.

Cumulus is the predominant cloud in the tropics. In fact, its average frequency is significantly greater here than anywhere on earth. In some tropical areas, cumulus clouds are present almost every day of the year.

Figure 2-13 shows that cumulus clouds occur more frequently in the Atlantic and Indian Oceans than in the Pacific, but, on synoptic grounds, this indication is suspect. Some evidence exists that local increases in frequency of these clouds, in the tropics, tend to correspond to the seasonal shifts of the equatorial trough line, but this is not enough to change the locations of the larger minima and maxima. The remainder of the seasonal changes are largely local in nature. The east coast of Africa, northwest of Madagascar, shows just such a change. Here, the percentage frequency increases from less than twenty per cent in winter to over fifty per cent in summer.



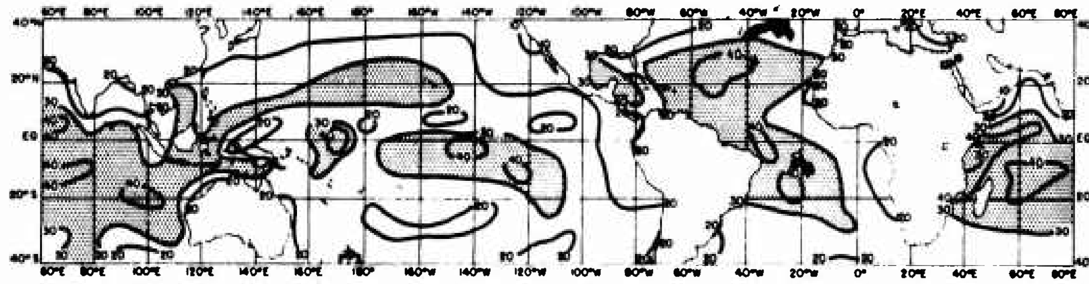
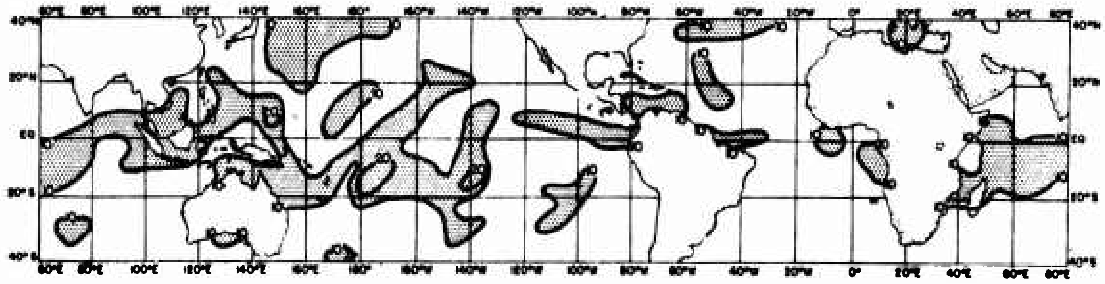


Fig. 2-13. Average frequency of cumulus clouds for the seasons. Dec., Jan., Feb., (above) and Jun., Jul., Aug., (below), in percent.

The average frequency of cumulonimbus over the tropical oceans for the winter and summer seasons is presented in figure 2-14. Over the open ocean



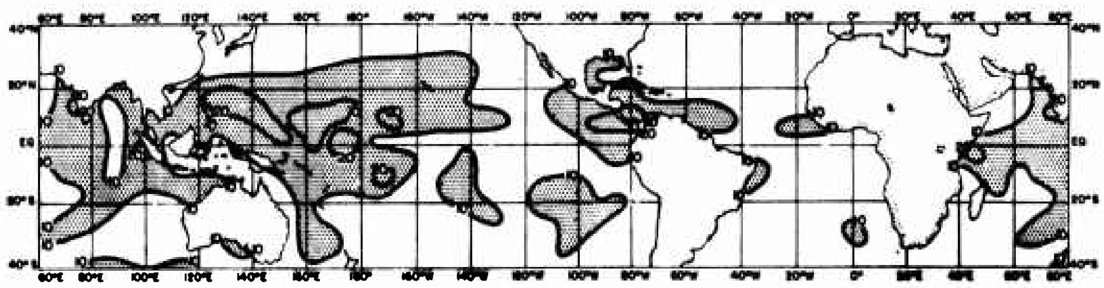


Fig. 2-14. Average frequency of cumulonimbus clouds for the seasons. Dec., Jan., Feb., (above) and Jun., Jul., Aug., (below), in percent.

cumulonimbi are most often found in the vicinity of tropical disturbances, while near and over the larger islands or land masses they are orographically produced. Figure 2-14 emphasizes the point that cumulonimbus clouds can be found everywhere in the tropics. The tropical Atlantic Ocean, however, shows remarkably few cumulonimbi in comparison to the other tropical oceans. The Central and Western Pacific Ocean shows the greatest frequency throughout the year. This maximum in the Pacific shows a remarkable relation to the average tracks of storms and typhoons (Figure 7-8). This is especially noticeable in the Western Pacific in summer, where the frequency shows a marked increase along latitude 10°N. To some extent, the same association with storm tracks is present in the South-central Pacific Ocean and in the Caribbean. The lack of seasonal variation of cumulonimbus clouds is not nearly as evident as with the cumulus, as shown in figure 2-13. For example, the occurrence of cumulonimbi in the Indian Ocean appears to be proportional to the development of the monsoon. In the Pacific, a definite maximum occurs in both hemispheres in the summer season. Central America and the adjacent oceans show cumulonimbi occuring twice as often in summer as in winter. The seasonal changes in the tropical Atlantic are considered to be insignificant.

The average frequency of stratus and stratocumulus over the tropical oceans for the winter and summer seasons is presented in figure 2-15.

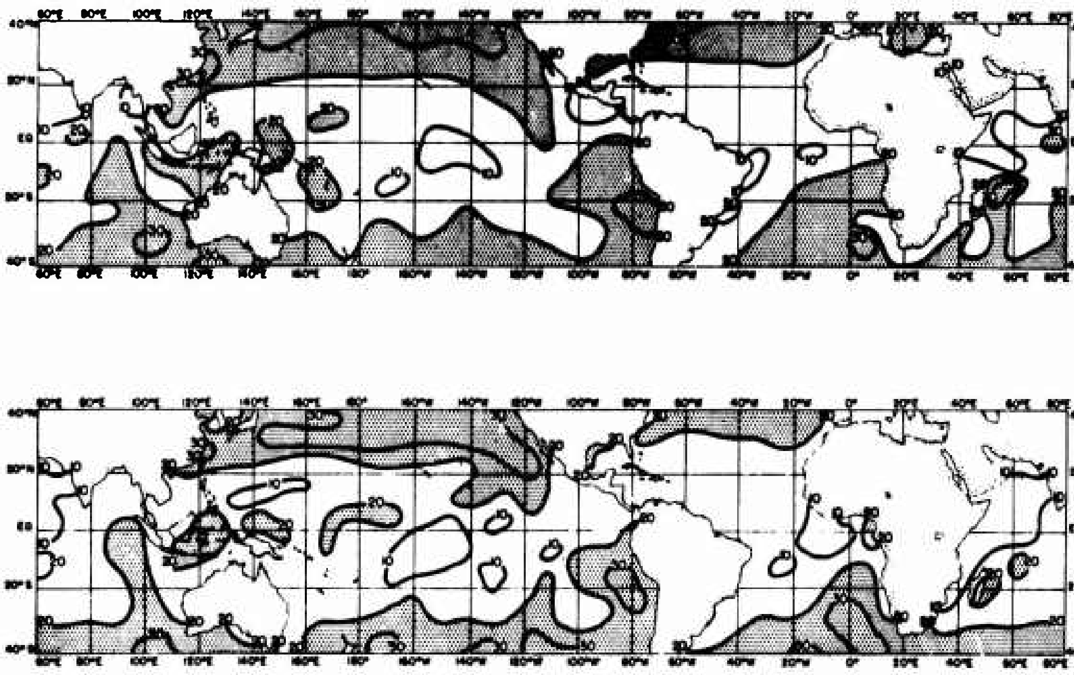


Fig. 2-15. Average frequency of stratus and stratocumulus for the seasons. Dec., Jan., Feb., (above) and Jun., Jul., Aug., (below), in percent.

Because of their similarity, stratus and stratocumulus have been grouped together. The figure shows that these clouds are rare in the tropics. The small percentage frequency may be considered an overall minimum, since the

shaded areas indicating over 20 per cent frequency occur at higher latitudes and effectively surround the tropics. In low latitudes, these clouds usually occur in conjunction with cumulonimbus and cumulus-congestus, mostly in patches; they hardly ever cover the sky from horizon to horizon. At higher tropical latitudes, forms of stratocumulus are sometimes associated with frontal structures that have penetrated the edge of the tropics. In such cases, the normal trade winds are disrupted, and the air masses involved are not truly tropical. The last significant feature shown by figure 2-15 is the lack of any seasonal effect upon the occurrence of these clouds.

2320. Tropical Rainfall Distribution. The general belief that frequent and heavy precipitation is one of the major characteristics of the tropics is only partially true. While it is a fact that the tropics as a whole receive more rainfall than other portions of the earth, the climatological record also shows that the annual amount of rainfall within its boundaries varies tremendously, both in time and space. The magnitude of these variations can be as much as 300 inches annually between two stations 70 miles apart. On a broader scale, another such variation is evident when comparing the annual amount of rainfall along the equator in Central Africa, as shown in figure 2-17.

As an example of a large time-variation in total rainfall we may compare two January rains at Fanning Island, lying 4° North in the Central Pacific. In January 1942, a total of 20.07 inches of rain fell at this station; the January 1943 total was 0.13 inches. Here there is no possibility of orographic determination of the rain, since the island is a small, low-lying atoll.

2321. Annual Rainfall Distribution. The zone of maximum rainfall in the tropics roughly lies along the equatorial trough; the minima lie along the usual position of the sub-tropical anticyclonic belt. Figure 2-16 shows these features very distinctly. Here the zonal distribution of annual precipitation, whether it be over land or water, shows a maximum very close to the equator. Secondary maxima are found near 50°N. and S., and are very likely due to the cyclone tracks in the belts of the polar westerlies.

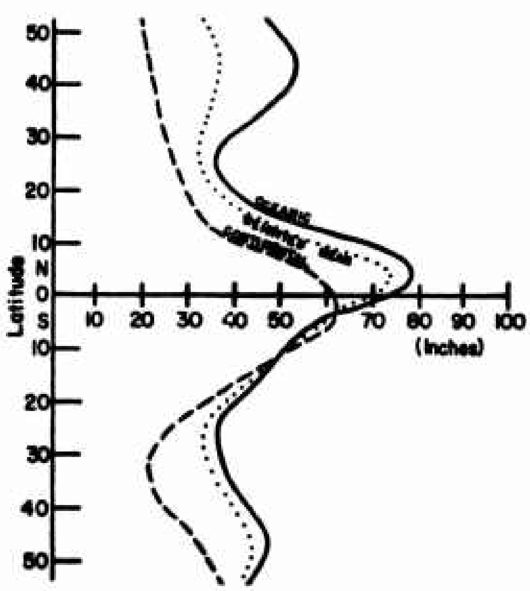


Fig. 2-16. Zonal Distribution of annual precipitation.

The tropics may be considered to consist of three basic rainfall regimes; (1) in the vicinity of the equatorial trough, characterized by rain at all seasons of the year, (2) in the trades, characterized by summer rains and dry winters, and (3) in the sub-tropical anticyclonic belt, characterized by dryness at all seasons of the year. Naturally, these regimes give only a very broad indication of the zonal

distribution of total precipitation. Specifically, within each region, the rainfall in any year may or may not fall within the scheme of classification. Statistics show that the Northern Hemisphere receives only two-thirds of its rainfall equatorward of 30°N., and the Southern Hemisphere receives even less in the equivalent area. This is partially due to the fact that the average position of the equatorial trough lies in the Northern Hemisphere and coincides with the mean zonal rainfall maximum. In the sub-tropics, the rainfall is found to be very nearly equal in either hemisphere. Figure 2-17 illustrates the patterns of minima and maxima of the annual precipitation. All

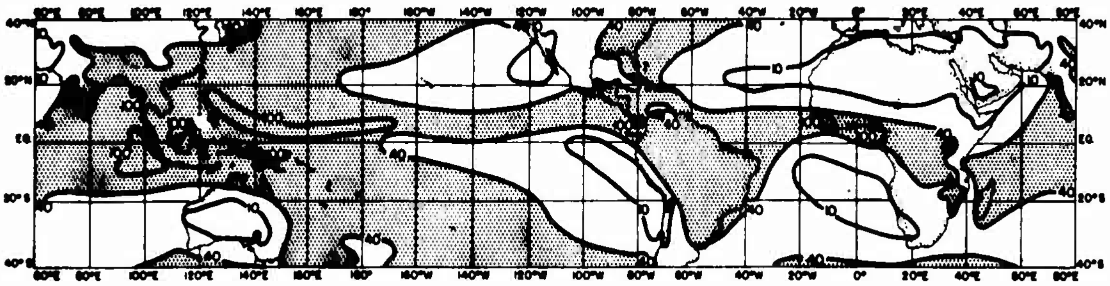


Fig. 2-17. Annual precipitation, in inches.

areas showing greater than 40 inches of rainfall per year are shaded. This shading can be traced around the earth near the equator, and individual maxima of over 100 inches are evident at frequent intervals in this belt. Similarly, a dry zone extends from Iran and Afghanistan, through the Arabian Desert and the Sahara, far out into the North Atlantic. In the Western Hemisphere, the dry regions of Mexico and the Southwestern United States form a part of this dry belt. In the Southern Hemisphere, the driest parts of the dry belt are found over Western Australia, South Africa and South America. A marked dry zone is situated just south of the equator in the Central Pacific. During the summer in the Northern Hemisphere, an area of heavy rainfall along the equatorial trough is bordered on its south side by an arid zone. The width of this dry zone is only a few degrees in latitude. These wet and dry belts are often interrupted by zones of higher or lower rainfall areas. A good example of this may also be seen in figure 2-17; the wet "tongues" on the western ends of the oceans in either hemisphere appear to extend poleward from the equatorial regions through the dry belts.

Indications of strong climatic gradients are evident when examining the isohyets at the boundary of the equatorial trough zone. shifts of the average position of this zone of as little as 2 to 3 degrees of latitude from one year to the next can produce extreme rainfall differences in the marginal areas.

<u>2322. Seasonal Variation of Tropical Rainfall.</u> The latitudinal profiles of rainfall, averaged by season over all longitudes, (Figure 2-18 A) show that, except in the neighborhood of the equator, rainfall in the warm season tends to exceed that in the cool season. When the continental and oceanic profiles are separated for each season, (Figures 2-18 B and 2-18 C), the migration of the rainfall associated with the equatorial trough is particularly evident in the continental profile. In the southern rainy season, the rainfall maximum over land occurs much farther south than the oceanic maximum (Figure 2-18 B).

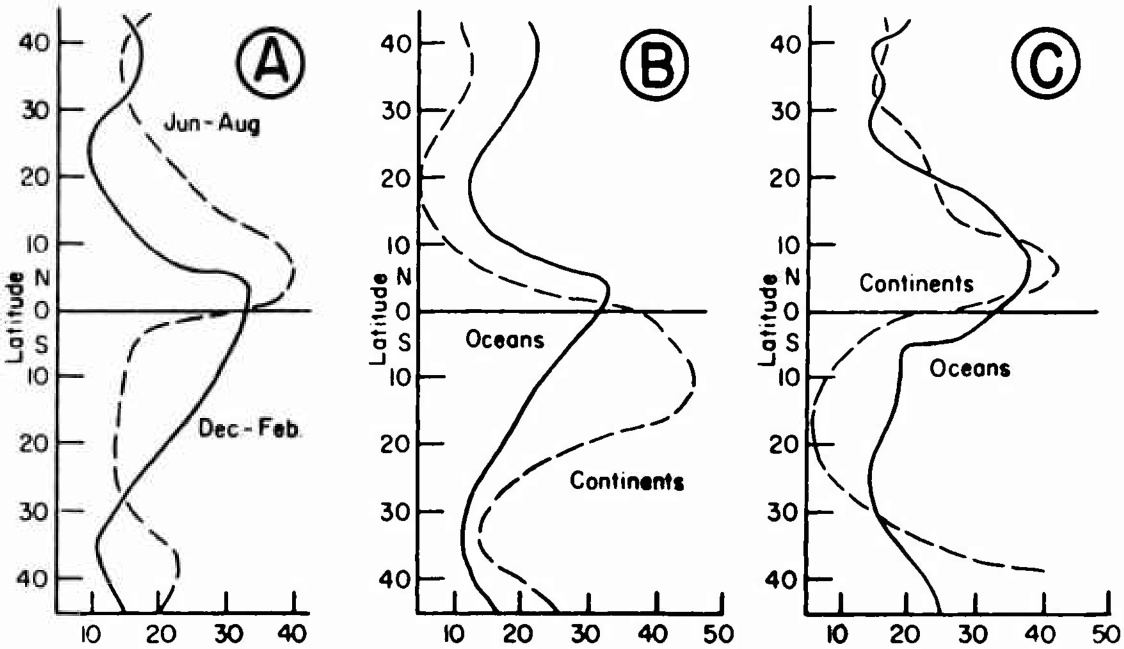


Fig. 2-18. Latitudinal profiles of rainfall, in centimeters per season. Left: Dec. to Feb. and Jun. to Aug. Center: Dec. to Feb., oceans and continents separated. Right: Jun. to Aug., oceans and continents separated.

The coincidence of rainfall maxima with the migrating equatorial trough leads to other seasonal correlations which are substantiated in principle by statistics from selected tropical stations around the earth. These show that as the trough reaches its extreme north and south latitudes in March and August, the equatorial margins of the trade-wind belt experience a single rainfall maximum, as shown in figure 2-19. Nearer the equator, where the trough passes any

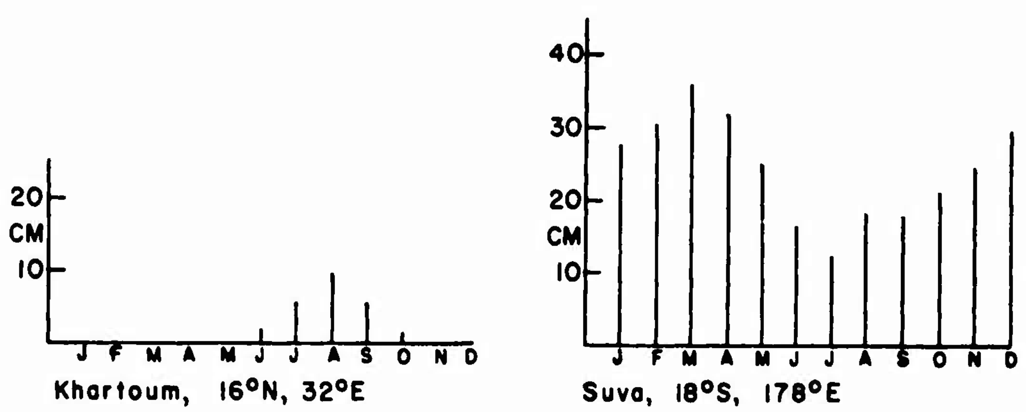


Fig. 2-19. Monthly rainfall at Khartoum, Anglo Egyptian Sudan, and Suva, Fiji Islands, in centimeters.

latitude circle twice annually, one finds two rainfall maxima. At any longitude where the trough is found to oscillate more or less symmetrically about

the equator, the heaviest rainfall is usually found near the equator from March to May and October to November (Figure 2-20).

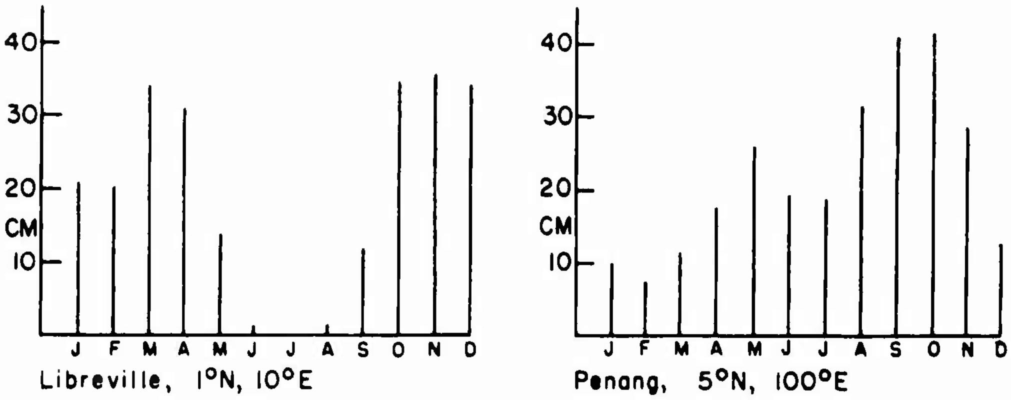


Fig. 2-20. Monthly rainfall at Libreville, French Equatorial Africa, and Penang, Federation of Malaya, in centimeters.

Outwardly, this appears to be a very simple explanation for the seasonal differences in tropical rainfall. Unfortunately, the position and motion of the equatorial trough at different longitudes around the earth is often vague and irregular. In addition, dynamic effects in the upper troposphere, including a close linkage of the tropical circulation with events in high latitudes, exercise an important influence (Section 2220). Considerable variations in the seasonal rainfall may then be expected from one part of the tropics to the other. This variability is low where the rainfall is high, and high where the rainfall is low.

Another departure from the seasonal variations shown on the profiles stems from the location of continents and oceans. In monsoon areas, air tends to flow from land surfaces toward water in winter, and from water surfaces to land in summer, and the pronounced seasonal variation in rainfall in such areas is attributed by climatologists to the orographic effects of seasonal shifts in the monsoon winds. The Southwest Monsoon in northern India indicates a single maximum of rainfall from June to September, but Colombo, Ceylon, (7°N.) near the southern tip of India, has distinct double maxima occurring in May and October. These maxima are attributed to the arrival and departure of the Southwest Monsoon in India. However, it is very difficult to apply such explanations to synoptic maps; for example, in Burma, short periods of heavy rain in the Southwest Monsoon often occur at times when the surface winds might be expected to suffer the least orographic uplift. In summary, a seasonal trend in tropical rainfall is very evident statistically, but this trend may be so masked or distorted that it is of little practical use in daily forecasting.

2323. Diurnal Variation of Tropical Rainfall. Tropical rainfall is subject to strong diurnal variations. This is particularly true over and near the coasts of the larger land masses where the land and sea-breeze regime governs the diurnal course of cloudiness and rainfall. Here the formation and motion of the clouds determine the location and time of the rainfall. The morning is generally cloudless, with small cumulus beginning to form inland.

During the remainder of the morning and early afternoon the cloudiness continues to increase and showers begin to fall. It is at this time, when the sea-breeze is best developed, that the maximum rainfall occurs over the land area. In the late afternoon and early evening, the clouds tend to dissipate inland and move or reform slightly offshore, where they reach maximum development at night when the land-breeze is strongest. Here again, a rainfall maximum occurs, but it is now found over the water. This pattern, with slight deviations, is often found to be quite regular in the tropics. If such characteristics of rainfall at a given station are identified, it is possible to make extremely accurate forecasts of the time and location of local rainfall.

The diurnal variation of rainfall over the oceans is a subject of some doubt. Haurwitz and Austin (1944) flatly state that the maximum occurs during the night or early morning, because convective activity over the oceans is greater at night than during the day. Riehl (1954), implies that in the areas of trade-inversions, the increase of low-level wind speeds and lowering of the trade-inversion at night would decrease the vertical thickness of the trade cumuli, a trend not easy to reconcile with an increase in precipitation. Until further evidence is presented, the practicing meteorologist should be cautious in assuming that rainfall over the open ocean reaches its maximum at night.

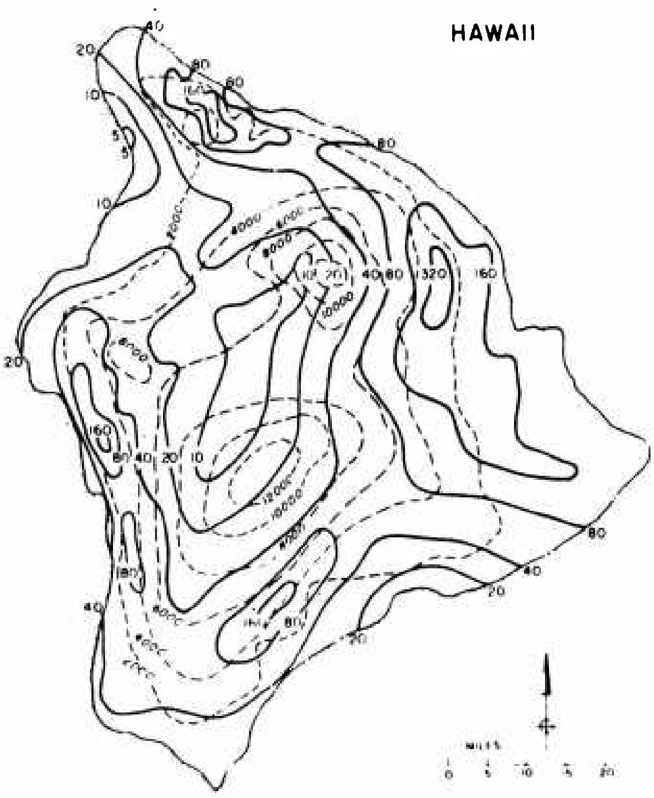


Fig. 2-21. Mean annual rainfall, in inches, Island of Hawaii. (Logarithmic spacing of isohyets).

The diurnal distribution of rainfall over the interior of continents generally has a maximum in the afternoon and a minimum during the night or in the morning. A large portion of the precipitation occurs in the form of convective showers and, since the tropics are subject to very intense solar radiation, the diurnal variation in convective activity is large.

2324. The Orographic Effects upon Tropical Rainfall. The exposure of any individual weather observing station, with relation to the local topography, often determines both the total annual rainfall and its seasonal course. Figure 2-21 is a particularly good example of how the total annual rainfall on the Island of Hawaii is dependent upon the

topography. This island is located in an area where the prevailing trade wind is from the northeast. The island consists of two mountains, each peak near 14,000 feet above MSL, oriented almost normal to the mean wind flow. The 320 inch isohyet is located at an elevation of 3,000 feet on the eastern side of the island, indicating that the maximum precipitation occurs here before the air completes its trajectory over the mountains. In contrast, almost the entire west coast of this island, lying in the lee of the mountains, averages less than 40 inches of rain per year. This tremendous contrast is found within a distance of 70 miles, and clearly illustrates how the topography can influence tropical rainfall. Naturally, the magnitude of the difference in rainfall amounts varies from place to place, and it is impossible to arrive at any general principle. The meteorologist must be familiar with the topography of, and the climatological statistics for, the particular areas or stations for which he forecasts. Maps of mean rainfall, particularly if the rain is classified by season or taken in conjunction with data on prevailing winds, constitute one of the most valuable forecasting tools provided by climatology. They indicate the regions of reinforcement and diminution of rain accompanying the traveling disturbances.

2325. Seasonal Frequency of the Various Forms of Precipitation. Until now, no distinction between the various types of precipitation has been introduced into the discussion. Familiarity with the normal distribution of these types, however, can be a valuable analytic aid in the forecast room. The widespread occurrence of precipitation forms which are statistically infrequent indicates that some type of synoptic disturbance may be in the area, even though at first sight the surface wind or pressure patterns seem to be undisturbed. For example, the occurrence of widespread thunderstorms in the trade-wind area southwest of the Hawaiian Islands might be the first indication of an upper level cyclone approaching the Islands. The surface winds in the area might show little change in direction from the "normal" trades, the only surface indication of a disturbance being a lessening of wind speed. Data on the upper winds probably would be lacking, so that the only indication of the upper disturbance would be a systematic arrangement of thunderstorms reported over an extensive area where normally the prevailing precipitation form would be the passing cumulus shower. On the other hand, in Indonesia, the suppression of the characteristic, widespread orographic thunderstorms would lead a forecaster working in that area to suspect some type of atmospheric disturbance in the neighborhood, particularly a disturbance accompanied by widespread descending motion in the middle troposphere.

The next four figures show the average frequency distribution, in per cent, of the various forms of rain observed at 1200 G.C.T.

The average frequency of rain in whatever form, (Fig. 2-22) shows that the highest frequency of rain occurs in a belt near the equator, roughly coinciding with the average position of the equatorial trough. Here also, can be seen two belts of low frequency that extend around the earth in the usual position of the tropical anticyclonic belts of both hemispheres.

The seasonal changes, except those areas affected by monsoons, are for the most part, slight. The monsoon is plainly evident over India and Burma, where the average frequency ranges from a value of less than 5% in December, January, and February, to a value of over 35% in June, July and August. Noticeable minima of rainfall lie just south of the equator (between the equator and 10° South) in the eastern portion of the Central Pacific. There is a tendency for a frequency maximum to be oriented along a line roughly coinciding with the average tracks of tropical cyclones. This is particularly true along a line

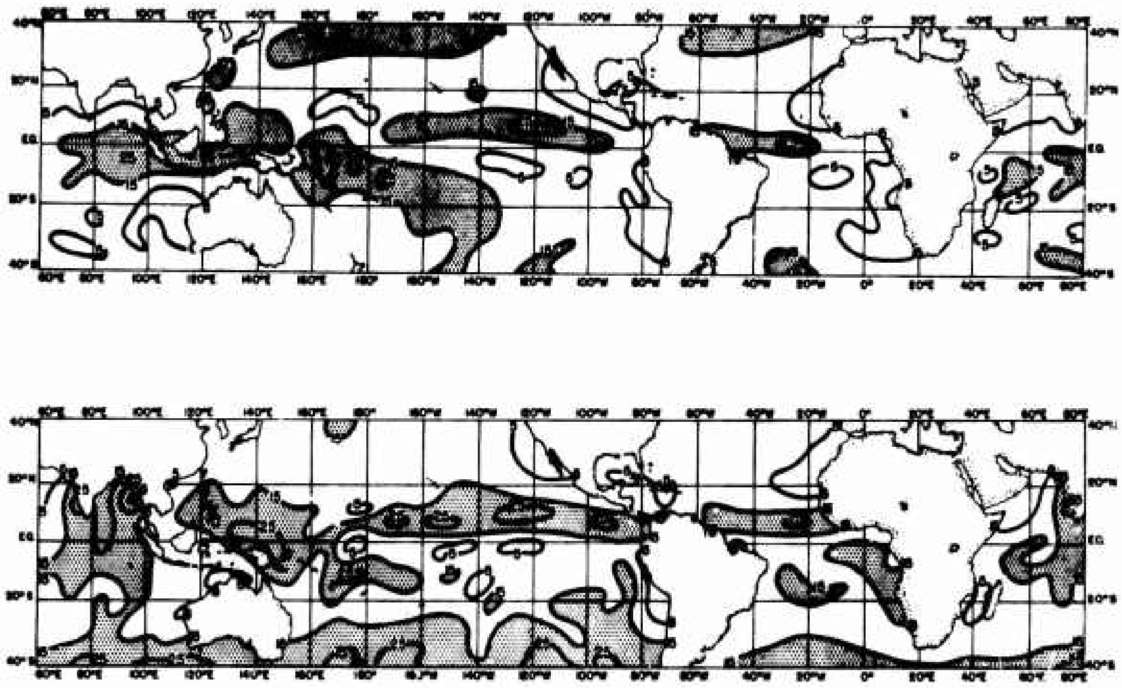


Fig. 2-22. Average seasonal frequency of rain in whatever form, December-January-February (above), June-July-August (below), in percent.

extending from Nauru to the Philippines in June, July and August, and East-southeast from the Solomons in December, January and February. This effect

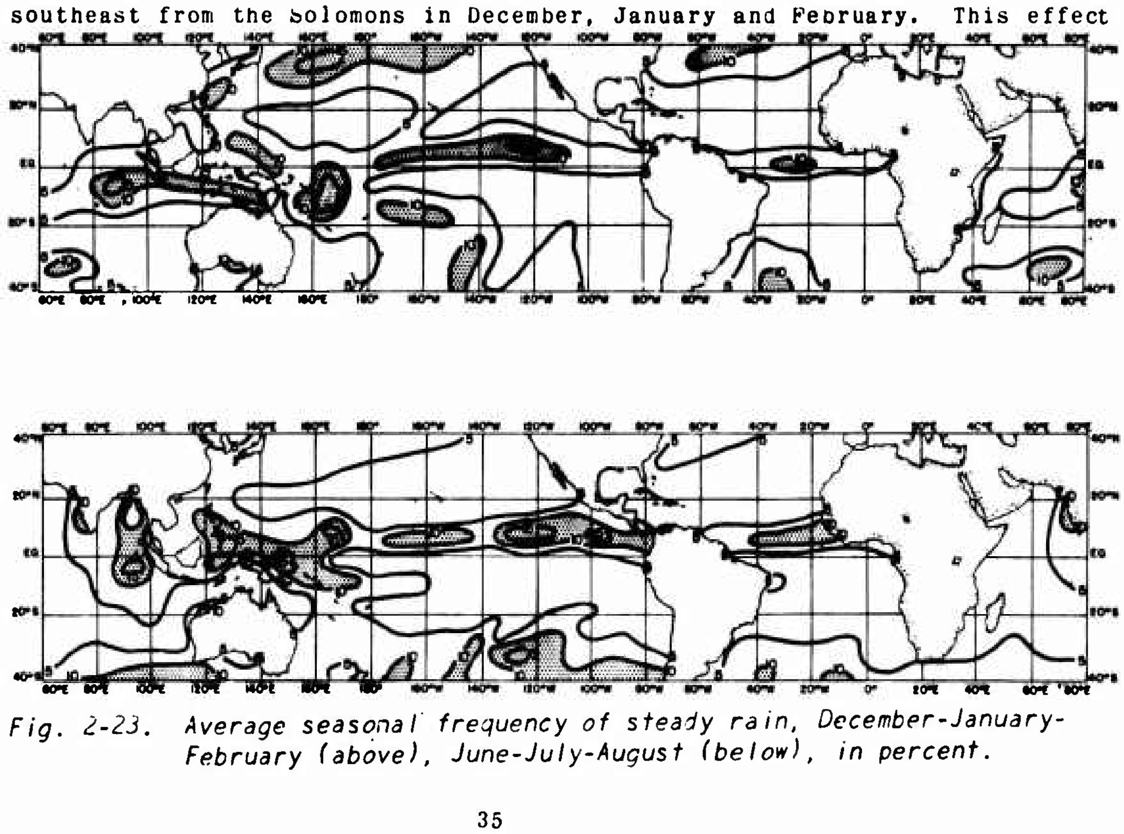


Fig. 2-23. Average seasonal frequency of steady rain, December-January-February (above), June-July-August (below), in percent.

2325.

is not nearly so noticeable in the Atlantic ocean.

<u>The average frequency of steady rain</u>, (Fig. 2-23). The figure indicates that steady rain is unusual in the tropics. Except for these low frequencies, figure 2-23 is similar to figure 2-22. Here again we find the belt of rainfall maxima coinciding with the average position of the equatorial trough, and larger, more obvious minima corresponding to the average positions of the sub-tropical anticyclonic belts in either hemisphere. The monsoon variation shows over India, and a similar effect is now evident in Northern Australia.

<u>The average frequency of passing showers</u> (Fig. 2-24) shows the same general patterns as the frequency of other types of rainfall with maxima and minima of the average frequency percentages coinciding with the average positions of the equatorial trough and the sub-tropical anticyclonic belts, respectively.

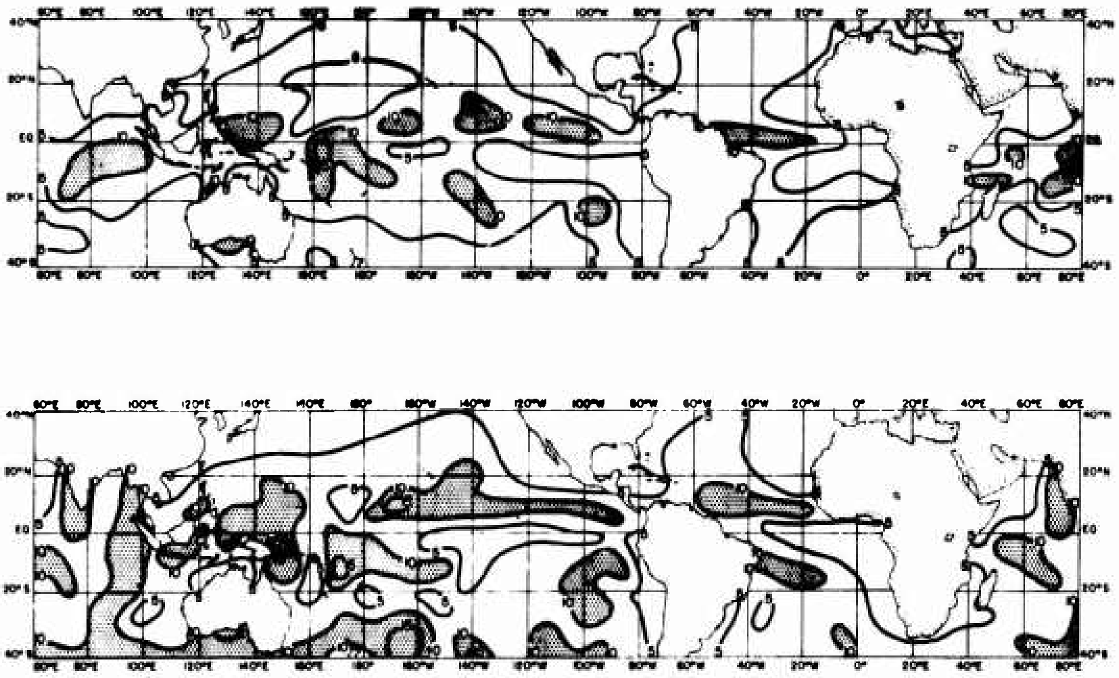


Fig. 2-24. Average seasonal frequency of passing showers, December-January-February (above), June-July-August (below), in percent.

Figure 2-25 shows the frequency of thunderstorms. The absence of any significant thunderstorm activity over the oceans is striking. Only those oceanic areas in the vicinity of island chains or coastal areas report frequencies that are worthy of mention. Such a belt of thunderstorms extends southeastward from the China Sea, across New Guinea and into the tropical islands in the South Pacific Ocean. If we consider that the major portion of the tropics consists of open ocean, the popular concept of extensive thunderstorm activity along the equator is subject to modification. Large cumulonimbus clouds associated with moderate to heavy showers and occasional hail at higher levels are found almost everywhere over the open ocean in the Central Pacific. It is interesting to note, however, that the lightning and

thunder which one would normally associate with this type of cloud and precipitation are often completely lacking.

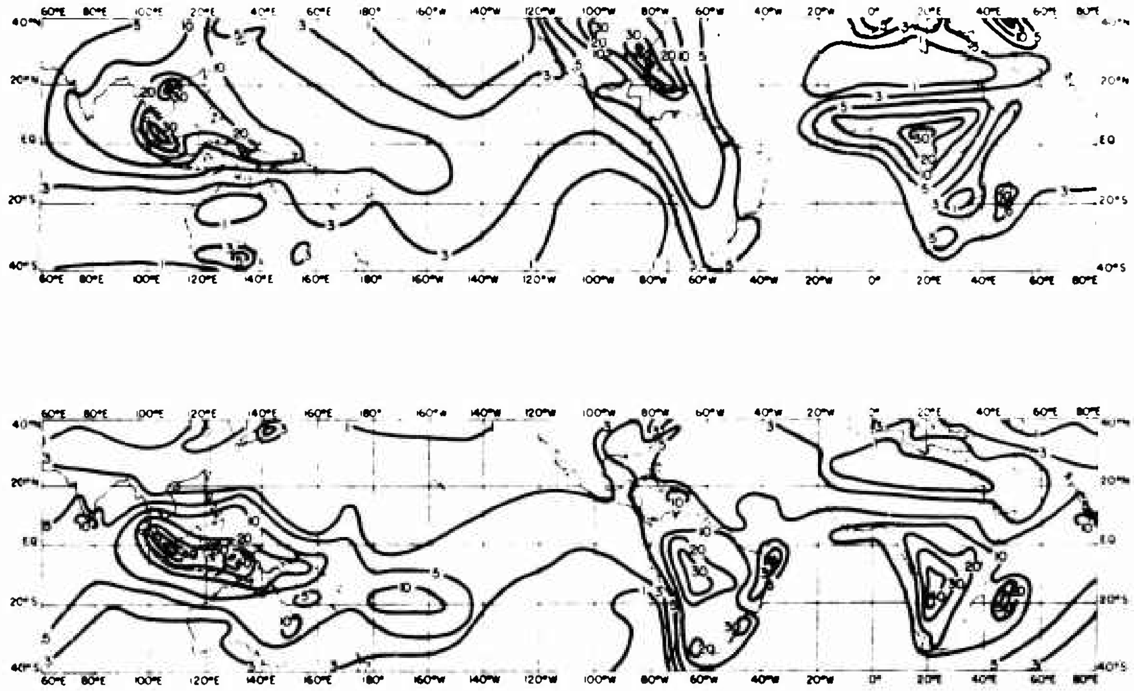


Fig. 2-25. Average seasonal Frequency of Thunderstorms for April-September (above), and October-March (below), in percent.

Figure 2-26 shows the mean zonal distribution of the percentage frequency of thunderstorms throughout the year. Throughout the tropics, more than twice as many thunderstorms are observed over land as over water. The

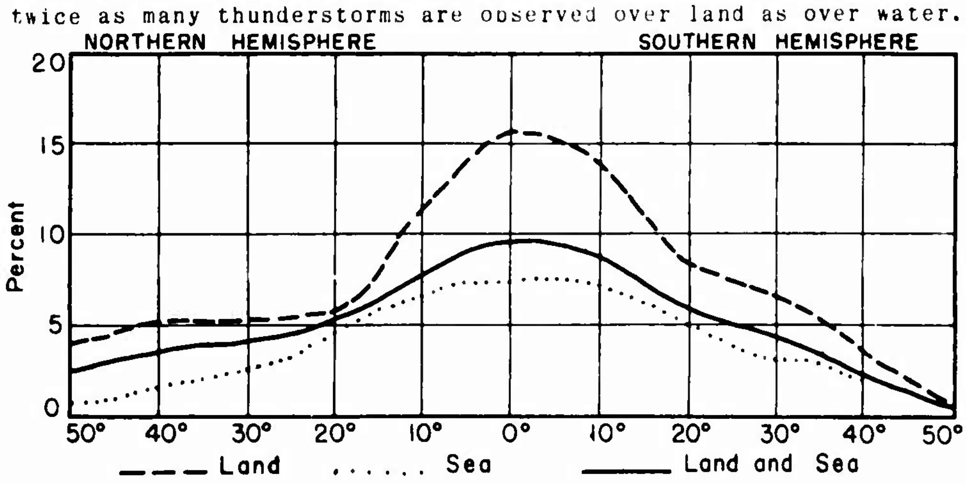
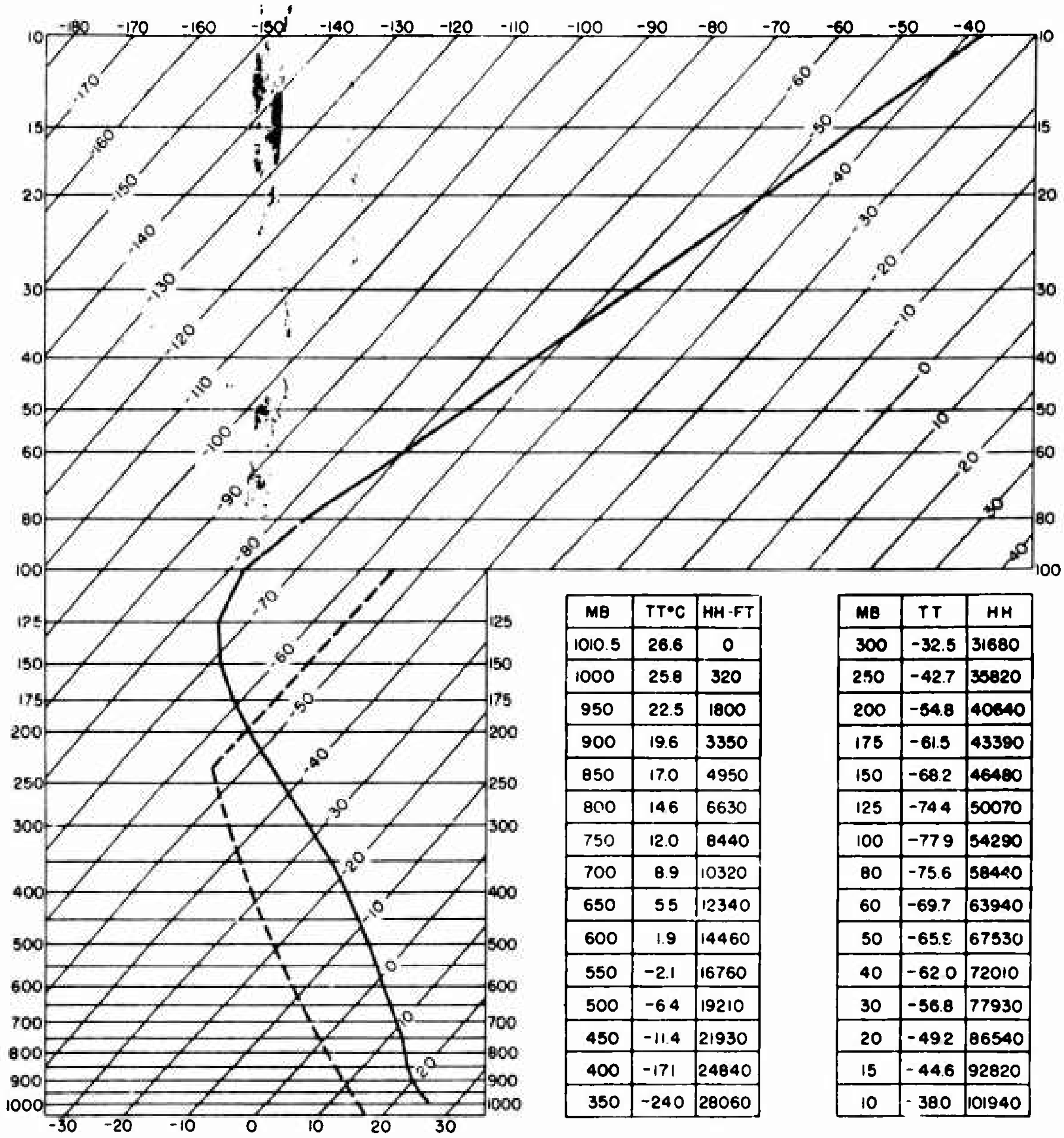


Fig. 2-26. Annual Zonal Distribution of the percentage frequency of Thunderstorms.

maxima of both curves lie at the equator; the oceanic curve from 20 degrees north to 20 degrees south, however, is flatter than the corresponding land curve

2400. MEAN TROPICAL LAPSE RATE.

Sufficient climatological data to create a "Tropical standard atmosphere" do not exist. Certain regional studies have been made in the Pacific and Caribbean for relatively short periods of time (climatologically speaking) from which a mean upper air sounding may be constructed with a moderate degree of reliability. Such a sounding is presented in figure 2-27.



MB	TT°C	HH-FT
1010.5	26.6	0
1000	25.8	320
950	22.5	1800
900	19.6	3350
850	17.0	4950
800	14.6	6630
750	12.0	8440
700	8.9	10320
650	5.5	12340
600	1.9	14460
550	-2.1	16760
500	-6.4	19210
450	-11.4	21930
400	-17.1	24840
350	-24.0	28060

MB	TT	HH
300	-32.5	31680
250	-42.7	35820
200	-54.8	40640
175	-61.5	43390
150	-68.2	46480
125	-74.4	50070
100	-77.9	54290
80	-75.6	58440
60	-69.7	63940
50	-65.9	67530
40	-62.0	72010
30	-56.8	77930
20	-49.2	86540
15	-44.6	92820
10	-38.0	101940

Fig 2-27. Mean Tropical Lapse Rate.

3000. EVALUATION OF THE DATA

3100. GENERAL REMARKS ON ANALYSIS.

Despite the recent development and extension of upper air observing networks and the application of new theoretical concepts to the data which they produce, modern synoptic meteorology still depends heavily upon the practice of air mass analysis. As carried on in most weather stations, weather forecasting is still largely a matter of identifying air masses, frontal boundaries and frontal waves and anticipating their transformations. Consequently, text-books of synoptic meteorology, and most courses of instruction, treat in great detail the origin, life-history, and interaction of the chief air masses, but pass over, more or less cursorily, internal air-mass processes which appear to be of secondary importance in forecasting the weather of high latitudes.

While some writers on synoptic theory have distinguished in the tropics a monsoon air mass, an equatorial air mass and a tropical air mass, in practice it is almost impossible to find any boundaries between them to which the criteria of a front can be applied with confidence. The whole tropical troposphere, with a few local exceptions, fulfills the standard definition of a single air mass. The synoptic meteorologist required to forecast weather in the tropics, then, is chiefly concerned with internal changes within this single air mass. While much of the high-latitude theory of air mass transformation is useful to him, he soon finds that it is not sufficiently detailed and that many weather changes, for example, those accompanying the origin and movement of tropical storms, cannot be interpreted in terms of frontal theory. He therefore requires a special treatment of the properties of the tropical air mass.

The practical aim of synoptic meteorology, the weather forecast, is the same in low as in high latitudes and however much the details of technique may differ, the general procedure is the same. It may be broken down as follows:

- The collection and evaluation of the data;
- The analysis of the data;
- The formation of a prognosis;
- The forecast.

In modern meteorology the term "analysis" has come to mean the result of the application of two distinct processes to the data. Obviously, the value of a particular meteorological element, say, the temperature, cannot be observed at every point in the atmosphere covering a region at some synoptic instant. The observations provided by stations in the network will be in the form of spot samples, referring to the air in the immediate neighborhood of the observing instruments and each sample thus taken will be far removed from others taken at the same time and in the same network. Even in the most civilized countries, possessing very dense networks, the samples are separated by scores or hundreds of miles. One of the chief objects of synoptic analysis is to reconstruct, from the samples, a graphical picture of the entire field of the meteorological variable over the region defined by the network. A perfect analysis of the temperature field, for example,

would give a continuous correct representation, probably in the form of isotherms at various levels such that it would be possible to read off the map or maps the temperature at any point in the space over the region and for that instant of time to which the analysis would refer. Analysis in this sense is an interpolation among the sampling observations; in principle, the observations are dispensable, once the analysis is completed.

If it were possible to observe the element at every point in the space of interest, analysis in this sense would be unnecessary; the meteorologist would already know the facts which the continuous analysis tries to represent. Analysis in the second sense, however, would still be necessary. The graphical representation would require interpretation. This part of the analytic process involves, at the present stage of development of meteorology, considerable experience and much empirical knowledge. The need for interpretation arises because theoretical meteorology has not reached the advanced stage required to compute future changes in any one continuous field from a knowledge of present and past conditions. For example, all the data collected over the United States during the past, together with accurate interpolations to give continuous representations of every field, (pressure, temperature, wind etc.) would not provide a quantitative basis for a computed forecast of the temperature field six hours in advance. Under the present circumstances, the synoptic meteorologist has to use generalizations from past experience, usually called "synoptic models", both to interpret the present situation and to forecast the future. He identifies these models during analysis and extrapolates them in time to arrive at the prognosis. Thus, in frontal meteorology both the "frontal wave" and the "occlusion process" are synoptic models; they sum up a vast synoptic experience and enable both interpretation of current maps and prognosis of future maps to be conducted in the weather station.

Since tropical meteorology is concerned with changes in a single air mass, synoptic interpretation is bound to be different from that applicable in higher latitudes. Moreover, the chief fields to which the interpolation process is applied in temperate latitudes are those of pressure and temperature; in the tropics other fields have to be analyzed and in one particular case, that of the wind field, the process of interpolation is more complicated and difficult than any necessary to a good air mass analysis.

The interpolation process would, in the ideal, be so applied to the observations that, for each synoptic hour, continuous graphical representations of the following fields would be available for interpretation and prognosis:

The pressure field.

The field of composition (dewpoint, visibility, cloud and precipitation).

The temperature field.

The field of motion (wind field).

To interpolate accurately among the observations of any one of these elements, the analyst must be sure that his data are not only free from error, but also representative on the scale of his network, that is, free from effects which are purely local. More precisely, he has the problem of determining whether his observations are a fair sample of the field under analysis. This task of critically evaluating the plotted data, of course, is encountered in air mass and frontal analysis in high latitudes. However, there are local effects which

are small and for the most part negligible in those regions, but which in the tropics are large enough to dominate over synoptic changes. If overlooked, they can lead to serious errors in the interpolative part of the analysis. They are for the most part orographic effects. Some local distortions of the temperature, dewpoint and wind fields, however, are not necessarily connected with mountains, or the differences between land and sea, but accompany the passage over the station of cloud and precipitation.

Evaluation of the data is also important in interpretation. Elements which ordinarily in high latitudes are conservative, that is, change very slowly with time during the transformation of an air mass, may change more rapidly in tropical regions. Moreover, their changes in the temperate zone may be attributable to one cause, while a very different cause may operate in the tropics. Thus, changes in dewpoint are usually slow within a single temperate-zone air mass and are attributable to the influence of the surface over which the air mass is moving. In low latitudes, certain rapid changes in dewpoint can occur within the tropical air mass which have little or nothing to do with the surface over which the mass is moving. If the usual high-latitude interpretation of a steep gradient in dewpoint is used unthinkingly, a tropical front which will have no objective existence may be drawn on the map.

For these reasons, the forecaster who is undertaking analysis in the tropics for the first time has to take special care in evaluating the data, at least until he has become thoroughly familiar with the geography of his region and with the often surprising local effects characteristic of the torrid zone. To assist in this process, the following points, raised in connection with the most commonly analyzed elements, should be kept in mind.

3200. EVALUATING THE SURFACE PRESSURE.

Surface barometric readings in the tropics may be unrepresentative in the same manner and for the same causes as those familiar to high latitude analysts. Mountain chains, particularly those oriented at right angles to the prevailing wind, produce a large, usually wave-like distortion in the surface pressure pattern over neighboring flat ground or sea surface and the distortion is found not only down-stream behind the obstacle, but also upstream, in some cases for large distances. When the mountain mass is very large as, for example, the Himalayas or the Rockies, the distortion is of such magnitude as to be regarded as a large-scale synoptic feature, subject to analysis and prognosis. In this case, it is incorrect to regard surface pressure readings in the flatter regions surrounding the mountains as being unrepresentative. However the same effects on a smaller scale exist in the neighborhood of all obstacles and have to be taken into account, particularly in oceanic analysis. In the Pacific, for example, many of the islands upon which weather stations are situated appear small and insignificant on the map but in fact they are rugged and of high relief. The island of Hawaii covers an area of only 4030 square miles, but there are two volcanic masses upon it, both reaching above 13,000 feet. The pressure at sea level on the windward coast of an obstacle as high as this can under certain circumstances, be as much as 2 mb higher and that on the leeward coast as much as 4 mb lower than the representative pressure, i.e., that which would be found in the region if the island were removed. Ignorance of these effects have led some novices in tropical oceanic meteorology to suppose that all barometers in low latitudes are unreliable.

Barometric readings, of course, are as much subject to error in the tropics as elsewhere; in fact, on remote islands or in sparsely settled continental regions, they are probably more likely to be wrong, chiefly owing to the difficulty of checking the instruments from some central place possessing standard barometers. There are several peculiarities of the tropical zone which tend to magnify the importance of any instrumental errors which occur. First, the observing network is very open. In some oceanic regions, the average distance between surface stations is about five hundred miles and there are many huge gaps in the network. The impossibility of checking the pressures by reference to neighboring stations, therefore, exaggerates the analytic effect of sporadic and index errors. Next, over great areas, particularly in the neighborhood of the equator, pressure gradients are very weak indeed, so that again the effect of an error is magnified. The weak equatorial gradients are exemplified by figure 3-1. In high latitudes, an error of 2 mb at a given station, while

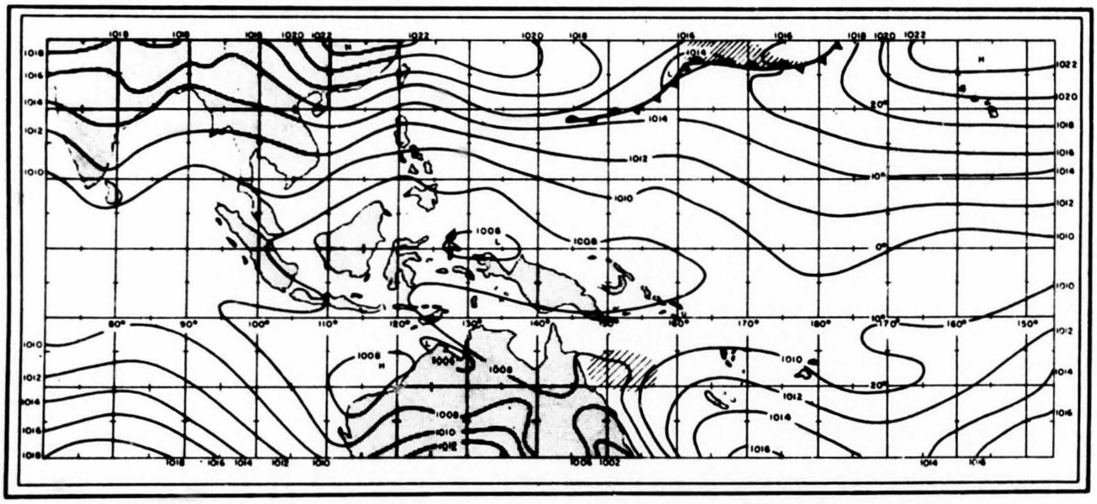


Fig. 3-1. Typical isobaric pattern over the tropical Pacific Ocean.

serious enough in a sparse network, would be unlikely to cause a qualitative error in the analysis; in the situation illustrated in figure 3-1, on the other hand, an error of this magnitude, say in the neighborhood of New Guinea, could easily result in the introduction of a fictitious low-pressure system; it could, under certain circumstances, lead to a serious error in the forecast. Finally, it should be emphasized that, over most of the torrid zone, the variations in pressure at the surface due to the passage of synoptic disturbances are only a small fraction of the semi-diurnal pressure variation. A typical barogram is illustrated in figure 3-2. The most marked feature of the barogram is the very regular semi-diurnal oscillation in the barometer. The amplitude of the wave is about 2½ millibars. Compare this with the general trend of pressure over the 4-day interval covered by the chart. There is, roughly speaking, a change over these days of 2 millibars; this synoptic change, then, averages 0.5 millibars per day. Though it is accompanied by real variations in the weather at the station, it amounts to only 1/5 of the semi-diurnal oscillation. Unless unusually favorable circumstances existed, it would be difficult in an open network to detect a synoptic change of this small magnitude by means of an analysis of the 24-hour isallobaric field. On the other hand, an error in time of observation, say of the order of two hours, might introduce into the routine pressure analysis an error of approximately the same magnitude as the synoptic change. Now the barogram refers to a station in relatively

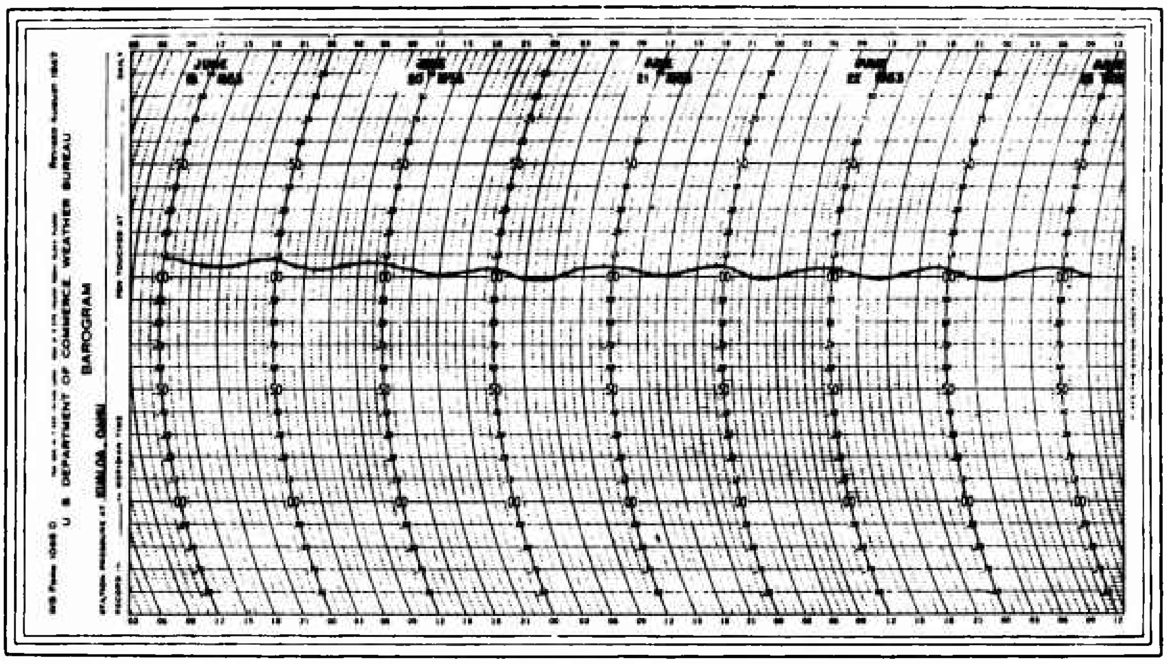


Fig. 3-2. Barogram from Kualoa, Oahu, June 1953.

high tropical latitudes (in the Hawaiian Islands). As one approaches the equator the amplitude of the semi-diurnal oscillation grows larger. At the same time pressure changes due to the passage of all synoptic disturbances, except the most marked tropical storms, become less and less. Thus in the Southern Marshalls the 24-hour pressure change which can be attributed to the passage of a single synoptic disturbance often amounts to only 1/10 of the diurnal oscillation in that region. The difficulty of surface pressure analysis, and particularly of detecting errors, is very great throughout the equatorial zone.

3300. EVALUATING THE VISIBILITY.

In dealing with visibility values in the tropics, the forecaster will become aware of the rapid fluctuations of these values during periods of shower activity. It is not at all unusual to find reduced visibility of less than 1 mile in an isolated shower, the shower being present in an area which has an overall visibility value of over 30 miles. It is not expected that the forecaster should be able to forecast the exact location of such showers, but he should at least be able to warn the pilot of their presence in an area and alert him to the possibility of the markedly reduced visibility values associated with rainfall.

Similar rapid deteriorations in visibility are sometimes observed in areas affected by coastal fogs and dust storms, although under those conditions the observations are generally more representative than those affected by showers, in that they may last for several hours, or even days.

3400. EVALUATING THE CLOUDS AND PRECIPITATION.

Observations of cloud and precipitation over the open sea far from any land mass are, of course, highly representative. This is particularly true of cloud observations made from an aircraft where a good view of an extended visibility field can be obtained; it is also true of the more limited observations possible from the deck of a ship. Low lying tropical islands, such as atolls or cays, also provide very good and representative observations. Although it has been claimed that atolls are sometimes covered by orographic clouds and that there is a diurnal variation in the frequency of precipitation, examination of the statistics from such stations, particularly those that extend over long periods of time, show that this orographic effect, if present, is of such small magnitude that it is unlikely to affect the operations of the analyst, nor need it be considered in the preparation of a forecast.

All other observations of cloud and precipitation, even those from quite small mountainous islands, have to be treated with great caution. The diurnal variation of cloud and rain, both over the continents and over the islands, is very large. The clouds form over, and often remain attached to, mountain chains, isolated peaks, relatively low ranges of hills, and even over small table-like islands not more than three or four hundred feet high (raised coral platforms). The direct effect of great continental deserts in the tropics and of massive mountain chains, such as the Himalayas, is so great that the relation between these features of the terrain and the atmospheric circulation in the region is evident even on the scale of the synoptic map. Here, obviously, the analyst needs to know the geography of the area with which he is dealing in great detail; otherwise he cannot hope to interpret cloud and precipitation observations. Nowhere is the effect of orography better illustrated than in the study of rainfall patterns, which in turn tend to reflect the variations in cloud distribution.

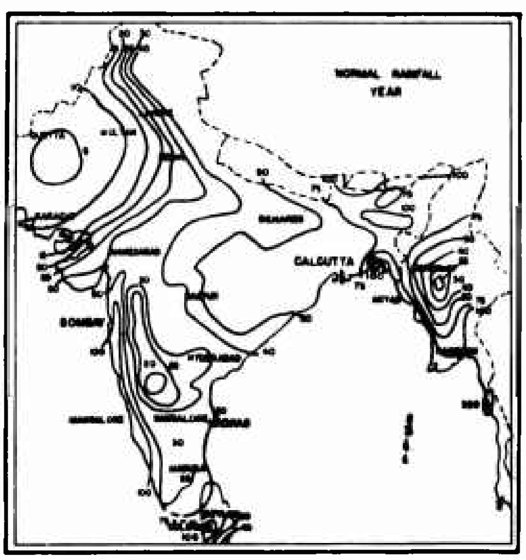


Fig. 3-3. Mean annual rainfall over India and Burma. (inches)

Figure 3-3, illustrating the mean annual rainfall over India and Burma, shows the extreme variations in rainfall in Northern Burma; stations only a few miles apart differ in their average rainfall as much as 100 inches. It is clear from this sample that an isolated report of precipitation can be without synoptic significance in one place but can be of the highest importance for analysis when it originates from a relatively "dry" station.

While the foregoing facts may seem self-evident when the discussion is restricted to the continental masses or to the larger islands, the analyst should not lose sight of the fact that effects just as extreme can occur in the vicinity of quite small but mountainous islands. This is particularly true when the islands occur in groups,

as in the Philippines, Indonesia, or the Solomon Islands. As an illustration, let us consider a diurnal cycle of intense vertical convection over such an island; for the sake of clarity, let us suppose the island is 20 miles wide and 100 miles long, with a single backbone chain of mountains rising to about 8,000 feet, the whole mass being oriented at right angles to the prevailing easterlies. About mid-day, even though there may be little cloud over the sea, large cumulus will have built up to a height varying between 8,000 and 15,000 feet above the mountain crest, depending on the latitude of the island and its position with respect to the semi-permanent oceanic highs. Already rain will be falling on the windward side of the mountain chain, and, as the afternoon progresses, the cumulus will spread horizontally along the chain and over the leeward slopes. At the same time the tops will grow into the higher atmosphere. Depending upon the latitude, time of the year, and other factors which need not be elaborated here, the tops, reaching their maximum development towards the middle of the afternoon, may grow to as little as 16,000 feet or to as much as 45,000 feet. If cumulonimbus is produced by this process, it may be accompanied by thunder and lightning, and, towards the latter part of the afternoon, will give rise to a great variety of clouds, such as altostratus, altocumulus, stratocumulus and various types of cirrus. From time to time, incipient cumulonimbus cells may become detached from the peaks and drift over the leeward side of the island; if this occurs, sporadic and isolated thunderstorms will briefly strike stations situated on the leeward plain and may even affect the neighboring sea downwind. By 7:00 or 8:00 P.M., the lower portions of the orographic cumulus, or cumulonimbus, will have vanished. Patches of cloud at the altocumulus and cirrus level, however, may persist. At the same time, or a little later, cumulus will be observed forming in a line parallel with the coast, usually on the leeward side. By about midnight, this oceanic cumulus will be quite evident to an observer on the leeward shore, and its dimensions and structure can be easily explored by aircraft on a moonlit night. If the diurnal cycle of convection is extreme, the oceanic cumulus will continue to grow during the night, reaching maximum dimensions just before dawn. Therefore, an aircraft taking off before dawn from a leeward airfield may find itself involved with a nocturnal thunderstorm off-shore at a distance between five and twenty-five miles, depending upon the terrain, season, etc. The mountain peaks may be quite clear of cloud at this time. Isolated cumulus or cumulonimbus, accompanied by showers, may drift toward the land from the pre-existing line, so that a leeward station may have a secondary maximum of showers between 6:00 and 9:00 A.M. local time. By 10:00 A.M., the off-shore cloud will usually completely disappear and the first orographic cumulus will begin to build up on the peaks; then the cycle is repeated with varying intensity, depending on the synoptic situation. During the whole of this cycle, the cloud over the open sea may show very little variation.

It should be emphasized that the formation of localized lines of off-shore cumulus or cumulonimbus, due to orographic effects, is most likely when several islands are clustered together in an archipelago. Under these circumstances, the cloud lines tend to form in the channels between the islands. Such lines are very common in Indonesia, the Philippines, the Solomons and, to a lesser degree, the Hawaiian Islands. It is clear that, if the analyst who is just beginning to deal with tropical weather and is unfamiliar with the geography of the area or with the characteristic diurnal cycles in such island groups, he may seriously misinterpret the reports from island stations and carry his misinterpretation into the forecast. He will particularly err if he interprets these local lines, which are, at most, 100 to 300 miles in length, as "fronts"

or lines of convergence of general synoptic importance, that is, if on his map he extends these lines for thousands of miles into regions of only sparse observation.

The tropical forecaster probably requires a deeper knowledge of orographic effects and of the geography of his region of interest than is usually required of a high latitude meteorologist. This knowledge is employed in two ways. First, it is used in deciding which observations are representative and in attempting to reconstruct, even from the unrepresentative data, what the conditions over the ocean or over the neighboring flat land (in the case of continental analysis) might be. Figure 3-4 is a sketch made from a color photograph of Tahiti, taken aboard the research vessel "Horizon" while approaching

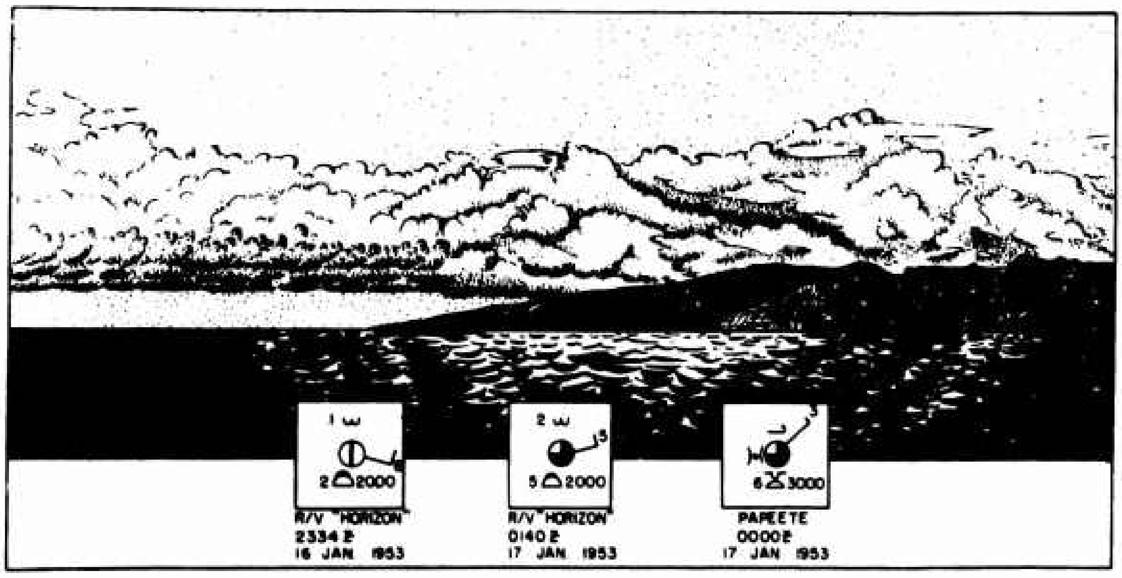


Fig. 3-4. Orographic cloud over Tahiti (from a photograph by Nicholson).

the harbor at Papeete at 2334 G.C.T., 16 January 1953. A weather observation was taken at this time, and another when the ship docked at Papeete two hours and six minutes later. These observations, plus the official 0000 G.C.T synoptic report from the weather station at Papeete, are shown in the figure. The sketch illustrates how unrepresentative an observation taken at Papeete, on the leeward side of the island, would be of weather conditions over the open ocean. Most of the cloud was situated over the island itself and was orographically determined; compare, for example, the mass of cloud stretching toward the leeward side, with conditions over the open sea. The weather observations taken at or near the time of the picture substantiate this feature. The "Horizon" reported only 2/10ths of cloud while still out at sea but reported 5/10ths when docked in the harbor approximately two hours later. For purposes of analysis, at least, we wish to correlate the conditions over the open ocean with the other fields under analysis.

Secondly, the analyst must employ the kind of knowledge exemplified in the previous paragraph in framing forecasts. Orographic effects have particularly to be considered in passing from the prognosis to a detailed cloud and rain forecast.

3500. EVALUATING THE SURFACE-AIR TEMPERATURE.

In the air mass and frontal analysis appropriate to high latitudes, the surface-air temperature is well known as one of the least representative and least conservative of all the meteorological elements. Standard texts on air mass analysis and air mass characteristics always emphasize this point. On the whole, we should expect the temperature to be less representative in the tropics than elsewhere and, over land, certainly less conservative. The intensity of insolation, for one thing, is greater in low than in high latitudes. Further, there is the difficulty of properly exposing the thermometers. Even a well-constructed aspiration psychrometer is difficult to use in the middle parts of the tropical day, and at stations well within the tropics the standard shelter fails to provide adequate protection from radiation on clear days. Moreover, close to the equator, winds are usually light, and it is almost impossible to aerate the sensing elements correctly without mechanical means.

While the difficulty of obtaining representative surface-air temperatures in continental localities has long been recognized, meteorologists are inclined to think that coastal and oceanic stations do provide representative temperatures. This is particularly the case when the stations are ship-stations or are located on small low-lying islands. For example, Petterssen (1940) states, "At sea the diurnal influences are negligible, and the temperature observations are always representative, provided that thermometers are well-exposed". In addition, he says, "Well-exposed coastal or island stations are usually representative. As a general rule, we may say that the temperature observations are most representative when the wind velocity is high and the sky is cloudy or overcast". While these statements are generally true in latitudes higher than 25°, there is an additional factor which tends to make surface-air temperatures unrepresentative over the tropical oceans, a factor which, so far as can be seen at present, is negligible in high latitude meteorology. This factor is the high frequency of showers within the torrid zone. Over the tropical oceans, by far the most frequent, though not the heaviest, precipitation falls in the form of showers from cumulus clouds whose tops are well below the freezing level. The effect of showery precipitation, both from cumulus and cumulonimbus, is twofold. With lighter intensities of rain, the falling water drops cool the air below the cloud base by evaporation. The resulting temperatures below the base are, after the shower has continued a very short time, close to the wet-bulb temperature of the surface air. Each shower is thus accompanied by a small "cold patch" as it moves over the observing station. After the passage of the shower, of course, the surface temperature quickly recovers its former value. The second effect is similar to that accompanying the downdraft under a thunderstorm. It accompanies all cumulonimbus showers in the tropics, all the heavier cumulus showers and, most remarkably, the heaviest rains from altostratus. In these cases a downdraft of cold air accompanies the heavy rain and may actually precede the shower and continue for a short time after the rain has passed. The surface temperature falls much below the representative surface wet-bulb temperature and is usually responsible, on atoll stations, for the minimum temperature of the day. In general, one may say that the heavier the precipitation the lower the minimum temperature attained.

Preliminary investigations in the Marshall Islands indicate that the temperatures begin to fall appreciably below the representative surface

3500.

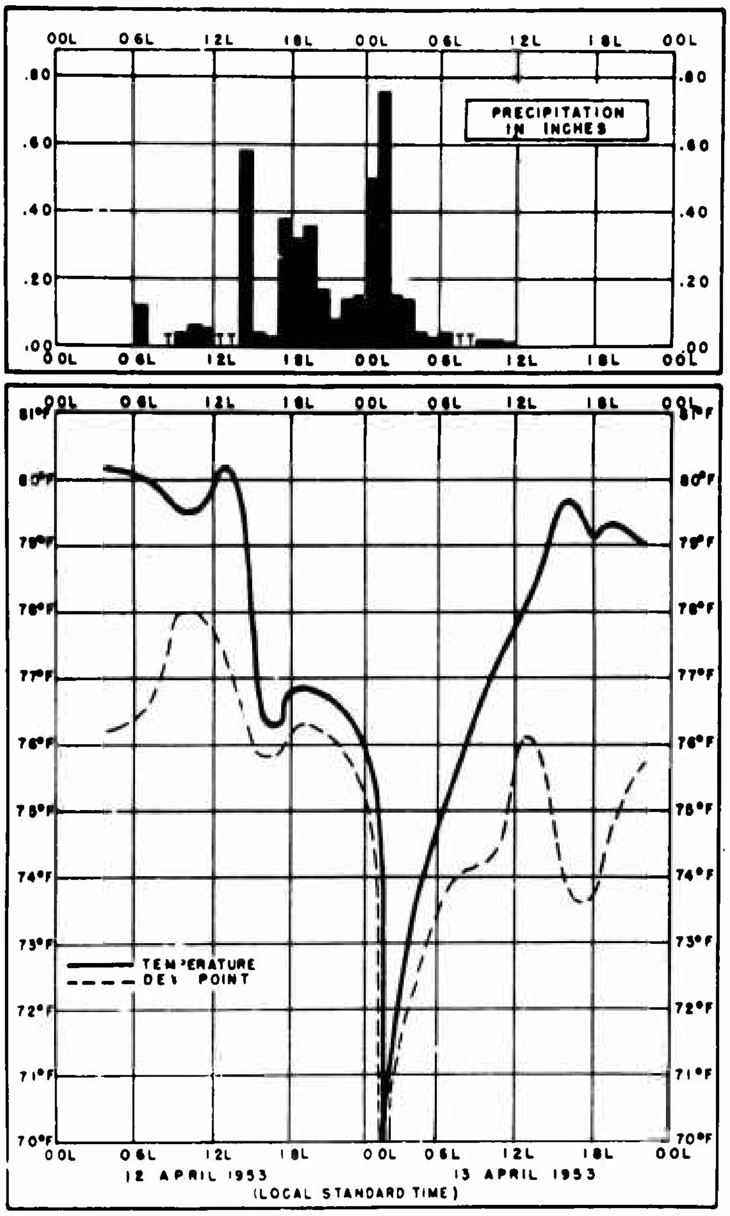


Fig. 3-5. Precipitation, temperature and dew-point, Canton Island.

wet-bulb temperature when the intensity of rainfall equals or exceeds one-hundredth of an inch per minute. Some remarkable instances of low temperatures accompanying heavy rain are known. For example, the record low temperature at Canton Island (3°S, 172°W) is 70°F., a minimum which was attained during the early morning of the 13th of April 1953. The hourly temperatures, wet-bulb temperatures and rainfalls at Canton Island on that date are recorded in figure 3-5. The observer reported strong, cool gusts from time to time during the period in which minimum temperatures were attained; the prevailing wind before and after the gusty period was, however, only 10 knots. In fact, the observer remarked that meteorological events during this time resembled closely those obtaining during the passage of a thunderstorm, but without any sign of thunder or lightning. The most remarkable feature of the weather was the fact that no cumulonimbus appeared in the vicinity. There are unequivocal observations to show that throughout the period of heavy rain the ceiling did not descend below 6,000 feet and most of the time was well above this. The observations indicated that the rain fell from a continuous, thick, altostratus sheet. Similar observations, less spectacular than these, have been made in the Marshall Islands. There can be no question of orographic effects, since Canton Island and the Marshall Islands are atolls.

The local nature of the cooling, whether it be light rain which lowers the surface-air temperature, or rain of the heavier type from large cumulus, cumulonimbus or thick altostratus, is shown by observations made at Eniwetok. As an example, we may briefly recapitulate events at Eniwetok on the 20th of

October 1952. The upper curve on figure 3-6 represents the surface-air temperatures taken on board the research vessel "Horizon", on station 20 miles off Eniwetok. The lower curve is a similar surface-air temperature record from Eniwetok weather station. Between 0000 and 0600 the temperatures of the two stations agree within 2°. At 0600, the temperatures at both stations begin to rise. The rise continues at the "Horizon", reaching its peak of 90° at 1300. However, that at Eniwetok does not exceed 85°. The maximum difference between the stations is attained at 1400 and amounts to 9°F. The significance of these temperature differences can be associated with the weather at the two places. It begins to rain at Eniwetok between 1000 and 1100; no rain is recorded during this period at the "Horizon". Eniwetok experienced heavy showers in the period 1300 to 1400, at about the time when the maximum difference in temperature between the two stations is recorded. Note the big fall at Eniwetok between 1300 and 1400 and a similar, but rather smaller fall at the "Horizon" between 1600 and 1700. These changes might be interpreted, and in fact have in the past been interpreted, as changes due to the passage of "fronts". Experience in the tropics, even of very limited extent, is sufficient to show that this interpretation is untenable. The temperature changes accompany showers which can be seen advancing toward and over the station. The showers often are so local that stations a mile apart will have quite different temperature traces. As an illustration, let us consider events at the research vessel "Horizon" and at Eniwetok on the 25th of October 1952, as shown in figure 3-7 on the next page. The records overlap for the period 0800 to 2300 local time. During this time the research vessel "Horizon" was within sight of Eniwetok Island; in fact, it was making runs in the lagoon of the atoll in connection with a seismic research program. At the beginning of the period, the temperatures of the two stations again agree within 2°F; both stations record rain at this time. The rain ceases at 0900 and the temperature climbs at both stations. Note that, as before, the "Horizon" temperatures are slightly higher than those at Eniwetok; this is probably due to instrumental error or bad exposure of the ship's thermometer. Showers begin at the research vessel at approximately 1300, although sporadic precipitation close to the ship was reported earlier. At Eniwetok station, however, there is no rain and the temperature continues to rise, reaching its peak of 89°F. at 1300 and 1400. Then follows the abrupt fall in temperature at Eniwetok after 1500, a little before the onset of the showery period. No possible orientation of "fronts" in the atoll lagoon could account for these changes. It must be emphasized that the observations displayed in these two figures (3-6 and 3-7) were not taken by extraordinarily skilled personnel.

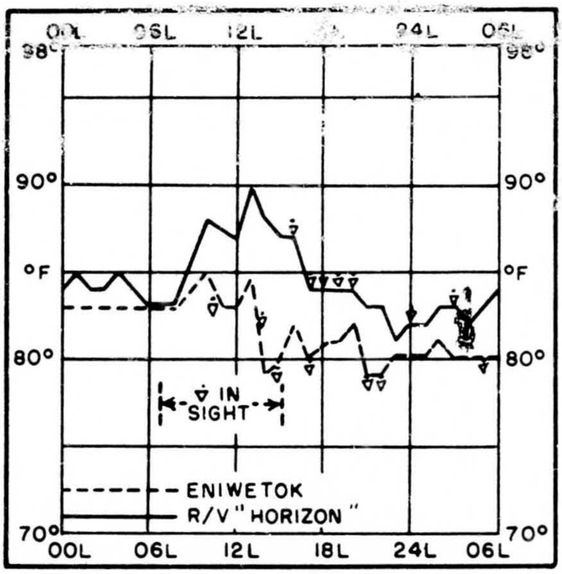


Fig. 3-6. Temperature and precipitation at Eniwetok and aboard the "Horizon", 20 October 1952.

Those on the vessel "Horizon", for example, were taken on the bridge by the officer on watch, and the thermometer hung in the wheelhouse -- a rather poor exposure, which probably accounts for the 2 degree difference in temperature between the "Horizon" and Eniwetok station.

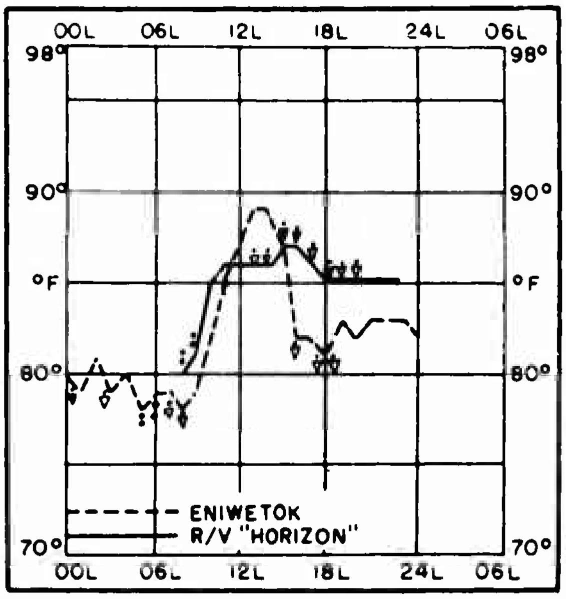


Fig. 3-7. Temperature and precipitation at Eniwetok compared to that aboard the research vessel "Horizon", 25 October 1952.

From numerous experiences of this kind, both at atoll stations and on shipboard, one must conclude that there is an additional factor in the tropics, over and above those considered in high latitude analysis, which makes for unrepresentative surface-air temperatures. Even the lightest rain will cause a fall in temperature, but the fall is purely local and moves with the shower. It follows that changes in surface-air temperature associated with rain, even when the reports are received from stations which ordinarily would be considered to have perfect exposure are quite unrepresentative. Even a cursory examination of a meteorogram upon which continuous traces of temperature and rainfall intensity are displayed on the same time base will convince the most skeptical of this fact.

3600. EVALUATING THE SURFACE DEW POINT.

It is a general principle of standard air mass analysis that the surface dew point temperature is more representative than the surface-air temperature. It should be remembered, however, that the dew point is not entirely free from local influences, especially over the large land masses. In a continental humid region, the dew point usually reaches its maximum during the afternoon, the minimum occurring in the early morning. Over deserts, on the other hand, the diurnal variation in dew point is the reverse of this. These effects are to be attributed ultimately to variations in the vapor pressure gradient close to the surface of the earth under continuously varying conditions of insolation and radiative cooling. In tropical continental regions, one may expect the same local effects as in higher latitudes, modified to take into account the greater intensity of insolation during the day. The analyst in oceanic tropical regions, also, should remember that the dew point is likely to be strongly affected by the situation of the station with respect to high, steep mountain chains. Foehn effects being so large in the tropics, one may expect that the diurnal variation of dew point on the windward side of a large mountainous island will be similar to that found under humid continental conditions. On the lee side, however, a station may record quite marked variations in dew point associated with descending relatively warm dry air passing downwind from the mountains as a foehn. Here the diurnal variation in dew point is likely

to be of the continental desert type. In some lee side stations this type of variation can be quite as large as that in dry continental situations. The lee side of New Caledonia, for example, will often show, during the prevalence of strong southeast trade winds, a continental type of variation. However, these lee side stations often record a secondary afternoon maximum of dew point which is due to the influx of marine air under the foehn after the onset of a sea breeze. Even in the absence of precipitation then, the forecaster will find considerable variations of dew point which must be attributed to orographic causes.

Orographic effects on the dew point can readily be taken into account by an analyst familiar with the topography of his region and with the precise location of his stations. As soon as rain falls at the observation point, the dew point becomes quite unrepresentative for other reasons. We have already seen how unrepresentative the temperature may become during heavy rain and the remarks which applied to the temperatures found in downdrafts under cumulus or cumulonimbus apply with equal force to the dew point temperature. Moreover, even light showers will affect the dew point, for, since the air is quickly cooled to its wet-bulb temperature at the height of the shower, wet-bulb temperature, dry-bulb temperature, and, of course, dew point will coincide. The dew point temperature is notoriously non-conservative with respect to evaporation from falling rain.

The results of this and the preceding section then, may be summarized. Both temperature and dew point become unrepresentative in low latitudes for the same reasons as are discussed in standard texts on air mass analysis. Those effects which are to be attributed to insolation are apt to be magnified in the tropics as compared with other regions. Over and above this, both elements become unrepresentative in the tropics because precipitation is, on the whole, more frequent and heavier than in most parts of the temperate zone. This is particularly true of precipitation from convective cloud. The local nature of rain showers and the massive effects on the temperature which accompany them make for abrupt changes in temperature and dew point within the tropical air mass; these changes are not to be confused with those accompanying the passage of air mass boundaries.

When all the effects described in the last two sections have been taken into account, the tropical air mass over the ocean is seen to be extremely uniform in the lower layers. The representative surface-air temperatures in the tropical Pacific are always within a degree or two of the sea-surface temperature. Since the gradient of sea-surface temperature is so small within the tropics, a great uniform air mass is produced. This is the classical tropical air mass at its source.

3700. UPPER AIR (RADIOSONDE) OBSERVATIONS.

The mercurial barometer is the most accurate instrument used in synoptic meteorology. Surface pressure observations are usually of a higher order of accuracy than is absolutely necessary for isobaric analysis in flat continental areas. This is not the least important reason for the great prominence that pressure analysis has had in synoptic meteorology during the past 80 years. At the surface, as is well known, the pressure observations are subject to errors of less importance than those accompanying the observation of the surface wind. In high latitudes the surface

[illegible].

isobaric analysis is therefore a more reliable guide to the representative field of motion than are the spot observations taken by anemometers Unconsciously, during the great expansion of meteorology since air travel began, the meteorologist has adopted the superstition that all pressure observations are of this order of accuracy. He tends, for example, to think that the readings from an aneroid barometer in the chart house of a ship on the high seas, probably unchecked for many years, are comparable with those of the best mercurial barometer.

This faith in the accuracy of the Bourdon tube, as compared with the mercurial barometer, is perhaps not too serious in the synoptic analysis of high latitudes. The oceans of the temperate zone, at least, yield many surface pressure observations, and since the gradients are usually steep, these, upon critical evaluation, are usually sufficient to yield a basically unequivocal analysis. But when the same faith extends to the observations made by radiosonde in the tropics, the upper air analyst immediately encounters difficulties and contradictions. Although great advances have been made in the past few years in the design and mass production of sounding equipment, the principles upon which the instruments are constructed are such as to yield observations of pressure of a lower order of accuracy than those of the mercurial barometer. Similar remarks apply to temperature measurements aloft. The advances in the design of temperature sensing elements have been remarkable, so much so that they even record the fact that the sun is, or is not shining upon the instrument. This feature, we now know, partially accounts for the diurnal temperature and pressure changes aloft and further establishes the greater reliability and representativeness of observations taken at night. It is important however, that the analyst not forget that these observations are used in a manner quite different from that applicable to surface temperature measurements. The radiosonde flight is worked up by an integrating process. In the computations, small errors accumulate and their effect may be magnified as the higher levels of the flight are reached. The estimation of contour heights, for example, is such that consistent results in the high tropical troposphere and lower stratosphere are difficult to obtain. Apart from this, the meteorologist who is dealing with any wide area, comparable, say, with Europe or North America, has to contend with the fact that different countries use radiosondes of varying manufacture and design. The radiosonde used by the different military and civil services also vary in design and manufacture; furthermore, corrections for radiation are applied to some types of observation and not to others.

In the analysis of upper isobaric surfaces in temperate and high latitudes, these facts are taken into account. The order of accuracy of the instruments, the possibility of transmission and personal errors are to a certain extent allowed for in the <u>fineness</u> of the analysis that is subsequently performed. The isobaric surfaces, for example, are contoured at wide intervals, and the good analyst realizes that only major features of the isobaric surface can be mapped at high levels. In most regions, particularly over the continents, there are sufficient radiosonde observations to arrive at a general contouring of the 200 mb surface and the gradients on this surface in high latitudes are sufficiently steep to make the previously described sources of error of relatively minor importance. It cannot be too strongly emphasized that this is not the case in the torrid zone and over the ocean. The slope of the isobaric surfaces at all levels between 25°N. and 25°S. is so gentle that the effect of an error in either temperature or pressure measurement is enormous. It can, for example, make the difference between the drawing of a maximum or minimum point in the isobaric surface dependent upon a single observation. The matter is aggravated by the open nature of the tropical network. When approximately 1,000 miles intervene

between successive stations of the network, complete systems may be over looked, lost or reversed in nature during successive analytic periods.

The difficulty of contour analysis in low latitudes is enhanced by the fact that the standard methods of filling in gaps in the network, based upon theoretical assumptions about the dynamics of the flow, are also inapplicable. The use of the thermal wind relationship, for example, which is based upon the assumption that the winds are geostrophic, when applied to the use of shear vectors in differential analysis, quickly leads to fantastic discrepancies between the observed isobaric heights in the upper troposphere and those deduced through the use of thickness charts. This is undoubtedly to be expected on theoretical grounds, since the geostrophic wind assumption becomes less reliable as one approaches the equator. There is a further difficulty. Contour analysis is usually extended over oceanic regions by the construction of "ideal" lapse rates referred to surface ship observations. These ideal lapse rates are constructed in terms of synoptic models, of empirical knowledge of the normal lapse rates encountered in middle latitudes and of continuity (under the assumption that the temperatures are quasi-conservative in the free atmosphere). In the tropics this method will frequently break down, especially in those areas of greatest interest, the regions where there is wide-spread precipitation. Not only is the surface temperature affected by heavy rain, but so also are the temperatures in the sub-cloud layers. When an aircraft passes through a shower, the temperature will fall; if the shower is very heavy, there may be a relatively large fall in temperature. However, when the aircraft has emerged from the shower, the temperature will recover its former value. Figure 3-8 is a diagramatic illustration of the temperatures which would be recorded by an aircraft flying at 1,000 feet through a true front accompanied by rain, and one passing through the cool patches associated

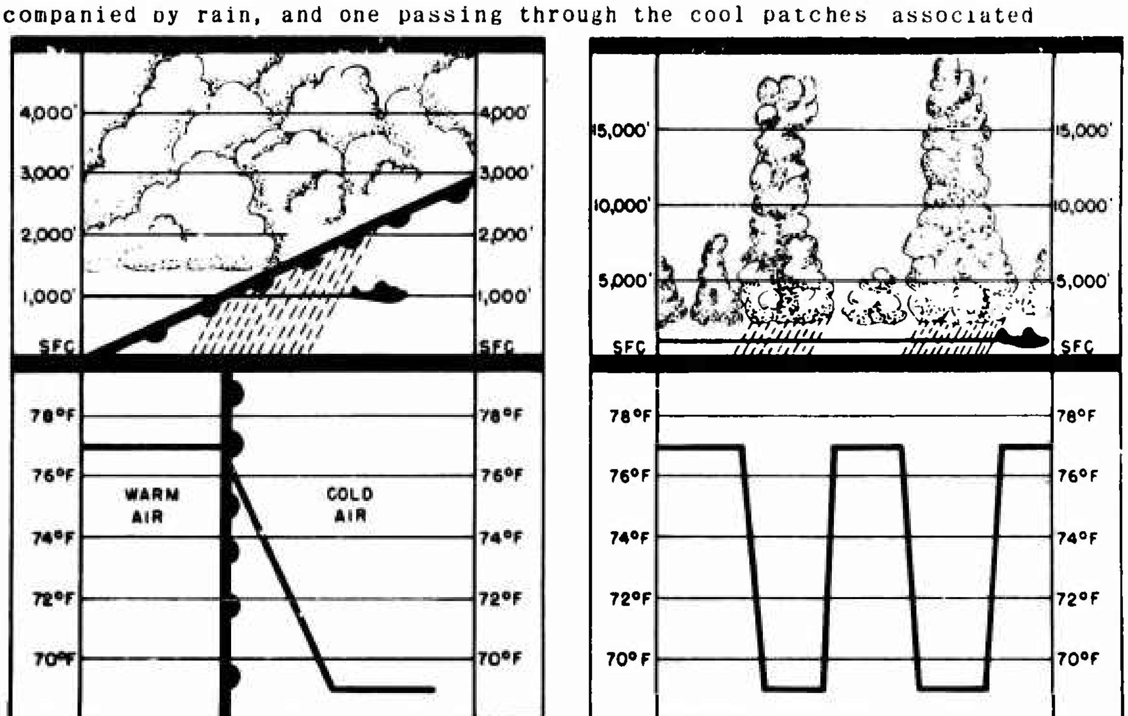


Fig. 3-8. Temperature changes encountered through a warm front (left) and Cumulus showers (right) at the 1,000 foot level.

with large precipitating cumulus at the same level. Observations at numerous stations in the Pacific show that temperature measurements in very heavy rain under altostratus are often unrepresentative up to 10,000 feet or more. As an example. We may refer again to the events at Canton Island during the heavy rain of 13 April 1953. (Fig. 3-5) At the period of maximum downdraft accompanying the heaviest rain, the radiosonde observations at Canton Island show that temperatures were affected locally up to 20,000 feet. Similarly, if a radiosonde happens to be released in the neighborhood of a large cumulonimbus and to pass in and out of the successive layers of secondary cloud associated with the convective mass, the temperature trace will not be the same as that of an instrument released a few miles away in clear air. Orographic effects themselves effect the radiosondes on mountainous islands. There are very puzzling discrepancies among the radiosondes of the Hawaiian Islands, for example, discrepancies which can only be explained in terms of local orographical effects associated with the high mountains near the various observing stations.

These difficulties have led some meteorologists to maintain that the radiosonde is an instrument of little or no value within the tropical air mass, so long as it lies in its source region. It seems to these meteorologists that the temperature measurements can be so unrepresentative and the errors both in temperature and pressure so large, as compared with the gradients they are supposed to detect, that contour analysis, in fact any type of pressure analysis, is a waste of time. Moreover, they say, the lack of representativeness in the temperature measurements renders the use of the soundings in local forecasting of cloud and precipitation misleading and even dangerous. The attitude taken here is that while all these difficulties are to be fully realized, tropical meteorologists should, if possible, persevere with both contour analysis and with the attempt to apply the soundings to local cloud and precipitation forecasting. Wherever the observations are dense enough (unfortunately in a very few areas of the tropics), contour analysis should be attempted. This is not to arrive at an idea of the field of motion, since this can be obtained more accurately by other means, but rather to investigate the pressure field itself at all levels. The pressure gradient is one of the most important dynamic parameters directly observed and if both an analysis of the field of motion and a pressure analysis of any accuracy are obtainable, the future possibility of computing the field of acceleration, and consequently the development of the weather, lies open. No doubt this will be a difficult task, perhaps insoluble with the present instrumental observing program. However, it will not be solved by omitting to take radiosonde observations altogether, nor by neglecting to study pressure-wind relationships wherever possible.

3800. EVALUATING THE SURFACE AND UPPER WINDS.

Consider a simple definition of the wind found in one form or another in textbooks of dynamic meteorology: wind is atmospheric motion relative to the earth. At first sight, this definition is adequate. Any region in which the atmosphere is moving through space with precisely the velocity of the underlying earth is a region of no wind, that is, calms; otherwise, there is a wind. Yet strict application of this definition would not only violate everyday experinece, but also invalidate a large part of the basic reasoning of dynamic meteorology. What do we mean by the expression "atmospheric motion"? What is moving? The kinetic theory of gasses implies that at all temperatures

observed on the earth, the molecules of the atmospheric gasses are in incessant random motion; in any region of apparent calm, countless billions of molecules are moving in all directions relative to the earth. Nevertheless, the molecular motion is not perceptible as wind. Clearly, before we can observe a wind, the atmospheric matter that is moving must consist of much more than a single molecule and there must be some kind of systematic movement of many molecules superimposed upon their random motion. The wind must, in fact, consist in the motion of a collection of molecules occupying a volume large enough to enable (at least in principle) measurements of temperature and pressure to be made within it, and yet small enough to enable the matter in it to be treated theoretically as a single moving particle. The instantaneous mean motion of the molecules within this volume could be defined as the wind at a point in space corresponding to the center of symmetry of the volume. For purposes of discussion we shall call the wind so defined, but never observed, the "true" wind.

The foregoing definition is based on theoretical considerations, and is dominated by the desire to avoid violation of our common experience. It is doubtless inadequate for some theoretical purposes. For us, however, the difficulties arising from it are practical; this wind is never observed in routine meteorological practice, nor is it ever plotted on a synoptic map. Perhaps the closest approximation to it which is attainable practically, is given by the observation of a hot-wire anemometer, or of finely divided matter, such as a very small cloud of ions, suspended in the air. But these methods still give only an approximation to the true wind. The meteorological "particle" or "parcel" would probably occupy at any instant a volume so small that any practical instrument used in observation would inevitably disturb the molecular motions within it. What would be observed then, would be the true wind with an added component due to the introduction of the instrument. However this may be, the observation of air movement by highly sensitive methods is still of great value; it gives us some empirical grounds for inferring the general properties of the "true" wind. The general result of this type of anemometry may be summed by saying that the more we increase the sensitivity and accuracy of wind measuring instruments, the greater become the fluctuations from one instant to the next in the observed wind. The inference is that the true wind is a violently fluctuating entity and that the atmospheric motion mentioned in the definition is always highly turbulent.

At this point we may pause to inquire whether in searching for a means of defining and measuring the true wind, we have not departed too far from common experience. The atmospheric fluctuations revealed by very refined and sensitive anemometers bear only indirect relationships to the motions called wind by the layman. He judges the direction and force of the wind as he knows it by observing the integrated visible effect of the fluctuating true wind on structures, vehicles, living organisms, loose surface material, and bodies of water. The synoptic meteorologist is called upon to observe and to forecast changes in this wind. The atmospheric motion to be plotted on synoptic maps, to be subject to analysis, and finally to be forecast, is therefore some kind of integral or average of the true wind, and this kind of average is somehow determined by the scale of manmade structures, of the larger living organisms and of waves on the ocean. In fact, the observed wind is always an average taken over some time interval and over some volume

fixed with respect to the surface of the rotating earth. This wind is treated as if it were observed at a point fixed with respect to the surface of the earth and at an instant in time.

In practice the volume and time intervals over which the averages are taken differ enormously from one type of wind measurement to another. The earliest and most primitive methods of wind measurements frankly made use of the layman's intuition. The Micronesian navigators, who in former times made long voyages in ocean-going outrigger canoes through the archipelagoes of the Marshall and Caroline Islands, measured wind forces as "one man wind", "two man wind" up to "four man wind", according to the number of men required to stand on the outrigger platform to prevent the canoe capsizing under sail. The Beaufort scale of wind force, similarly, was based upon the behavior of sailing ships and upon the reaction of ocean surface to various wind forces. In these systems the vessel itself was an anemometer and its sluggish reaction to any but the more violent long-period fluctuations of the true wind conveniently cut down the time of the observation of its behavior to a short period, usually of the order of a minute; the volume over which the average was taken, however, might be very large. The deep sea criteria for judging Beaufort wind forces, for example, depended upon the use of the full-rigged man-of-war as an anemometer. Beaufort force 3 was said to be (1874) "that in which a well-conditioned man-of-war, with all sails set and clean full would go 3 to 4 knots in smooth weather". The volume of air explored by such a ship was huge in comparison with that sensed by the head of a fixed anemometer on land. Moreover, the wind variation with the height up to the mast top influenced the behavior of the ship and the manner in which an experienced master would set the sails. Beaufort wind forces were also estimated from observation of the effect of the wind on the ocean surface or, in the case of land observations, on dust, trees, and buildings. It was specified that the field of observation was to be large -- in most cases it included all the surface effects visible from the observing station. A good observer would watch the effect of the wind for a fairly long period, say 3 to 5 minutes, before recording his data. In this system the volume over which the averages were taken was again huge; however, since surface effects only were observed, its vertical extent was small and varied with the force of the wind.

Compare a wind measurement at sea in terms of the Beaufort scale, with one made by means of modern ship-borne anemometer. By convention, the time interval for averaging the latter is one minute. Allowance has to be made for the motion of the ship under its own power, though this is often neglected -- to the detriment of synoptic analysis. The ship's anemometer is a much more sensitive instrument than the full-rigged sailing ship, for which the Beaufort scale was devised, but an increase in sensitivity of marine anemometry is not an unmixed blessing. Modern ships are generally larger than the sailing ship and they are driven through the water at relatively high speed. The volume of air explored by the anemometer is much smaller than the Beaufort volume, but the ship itself is still part of the observing instrument. Its presence disturbs the air movement, adding to it eddies that in the mean give an unrepresentative component to the wind at the anemometer head. After these and other difficulties are taken into account, the wind observed is probably no closer to the true wind, as previously defined, than were the older Beaufort measurements; it is just a different average with an added systematic error that varies with wind direction and speed. The same remarks apply to standard anemometer measurements on land. The anemometer record gives a wind that is not

more "accurate" than the older Beaufort measurements, but merely different, the averages being taken over different space and time intervals.

If these considerations show that what we call the surface wind comprises measurements that are hardly comparable from case to case, how much more difficult is it to compare upper winds observed by different methods. In all cases winds aloft are estimated by the observation of moving objects. The winds again are clearly space and time averages. Sometimes the space average extends over a tremendous volume. Winds estimated by the total drift of an aircraft between points 500 miles apart, for example, cannot reasonably be referred to a point in space; nevertheless, so-called loran winds are frequently plotted on synoptic maps at specified points and in analysis are compared with winds derived from the rawinsonde. Neither of these winds are the true winds contemplated by theoretical meteorology, but only the rawinsonde may reasonably be referred to a point.

At the outset, then, we ought to admit that we do not observe nor is the synoptician particularly interested in "true" winds, and that the problems of dealing with the observed winds theoretically are, in the present state of knowledge, completely impracticable. It follows that kinematic analysis that is, analysis of the field of motion, is largely an empirical science. Its object is to analyze and to forecast changes in average air movements as measured by the rawinsonde. Before such an analysis is begun, theory can say very little about what to expect on the maps. The most that the foregoing considerations can give is the warning that the "winds" treated in any analysis should be as near as possible comparable, that is, that the spaces and times over which the averages are taken by the observing instruments should be at least of the same order of magnitude. Multiple drift winds taken on board a reconnaissance aircraft, for example, should not be compared with "navigation" winds from a transient aircraft flying between two airports: they should not, in fact, be plotted in the same manner on the same map.

Although the averaging process carried out during the normal wind observation eliminates short period fluctuations, the data, particularly in the lowest layers of the atmosphere, can still be unrepresentative. Eddies of all sizes probably exist in the atmosphere up to the very large ones we study on the synoptic map, namely, cyclones and anticyclones. The object of kinematic analysis is to investigate and identify these large eddies. Smaller disturbances of the flow, such as are set up by difference between land and sea, for example, will, on the synoptic scale of reference, be eddies leading to unrepresentative observations of wind. In parenthesis, it should be noted that these medium-sized disturbances are by no means unimportant in synoptic meteorology. Their influence must always be considered in forecasting, particularly in local forecasting. But, in the large-scale analysis, the typical synoptic description of broad air-flow, they should be eliminated. For our purposes we may classify the medium-sized disturbances into three types: firstly, land and sea breezes; secondly, orographical eddies; and finally, what may be called precipitation winds. We shall discuss these in order.

In classical meteorology, the best examples of land and sea breeze circulations were always described as occurring in the tropics; the accounts found in standard textbooks are still trustworthy, but, it should be

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emphasized here, tend to oversimplify the nature of the circulations. Theoretically, the land and sea breezes should prevail on all islands and coastal areas in the tropics. However, the so-called sea breeze component of the wind is so small on atolls, even those within the doldrums, that even long series of statistics do not suffice to show them unequivocally. On certain atolls, with large individual islets, a barely significiant variation in the force of the wind between day and night is detectable. The variation is certainly too small to be taken into account in synoptic work, and so far as is known, is of no practical importance. Consider, for example, the statistics from the island of Penrhyn in the South Pacific, (the structure of the island is shown in Figure 3-9). The mean speed of the wind at 0800 hours local time for the period 1937 to 1942 was 9 knots; afternoon observations at approximately 1400 hours give a mean speed of 8 knots. Further, the mean wind speed in the 5 degree oceanic square centered on Penrhyn Island, from over 50 years of ship observations, is 9 knots. On the island there is no significant difference between the afternoon and morning wind directions and the differences in speed are certainly not of synoptic importance. As will be seen from the map, Penrhyn Island is a typical atoll and the island upon which the observations were taken is very low, the highest point on it being 50 feet -- the tops of the coconut palms. It might be argued that the islands on the reef are so small that they cannot possibly affect the wind, the area being heated during the day and cooled during the night being infinitesimal in comparison with the broad ocean. In order to see how large an island must be before it affects the circulation through the land-sea breeze mechanism to an extent significant to the synoptic meteorologist, we can refer to another island in the South Pacific, Niue. As may be seen from Figure 3-10, this island is not an atoll, but is a more or less flat coral plate, not enclosing a lagoon. Here one might expect, on theoretical grounds, a marked land and sea breeze regime. However, the only affect that can be detected in the statistics is a tendency for calms during the night and early morning hours in July and August. There is no significant difference in wind direction between the morning and afternoon observations, but the mean speed in the early morning is 5 knots, in the afternoon 9 knots. Note that the observing station Alofi is on the westward or lee side of the island and that probably the wind that reaches this station is somewhat diminished by surface drag over the coral surface. This is borne out by the fact that the average wind speed over the neighboring ocean is 12 knots. Even an island as large as this, then, although a "land breeze component" can be detected in the statistics, does not provide an area

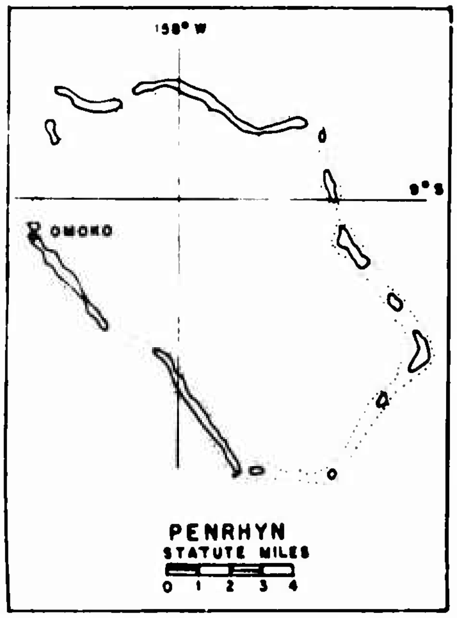

Fig. 3-9. The Geography of Penrhyn Island.

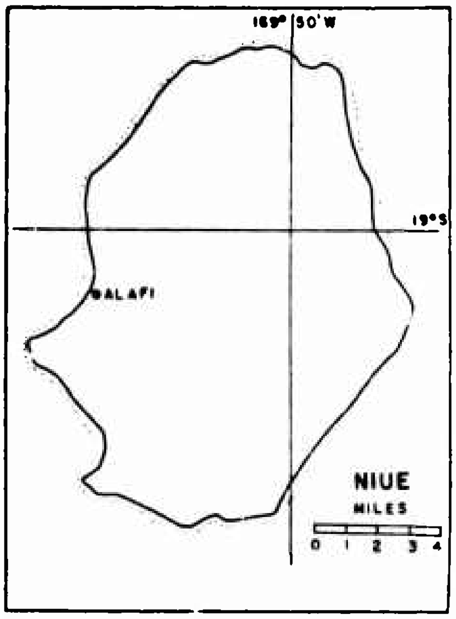

Fig. 3-10. The Geography of Niue.

large enough to give the well-developed land and sea breezes of classical tropical meteorology. At all events, the difference in wind speeds between night and day are not such as would need to be taken into account in synoptic analysis.

The situation is very different when the island is of high relief. The best-developed land and sea breezes are found on tropical islands which have high mountain peaks in the interior. Take, for example, the station Papeete on the leeward coast of the Island of Tahiti, figure 3-11. As an example, we may refer to the statistics for July and August. The frequency of calms at 0800 local time is 83%; at 1200 local time, 1600 local time, 36%; and at midnight, 77%. Contrast this with the frequency of calms over the open sea in this area and for the same time of the year; the frequency is approximately 5%. These statistics on calms only emphasize the conclusion which may be derived from a study of the variation of wind direction and force at various hours of the day. During the afternoon there is a pronounced shift of the wind towards northerly directions, while the mean wind over the sea is from the east and southeast. A study of islands throughout the Pacific, especially in the Hawaiian, Fijian, and Indonesian areas, shows that land and sea breezes are best developed on the lee side of mountainous islands.

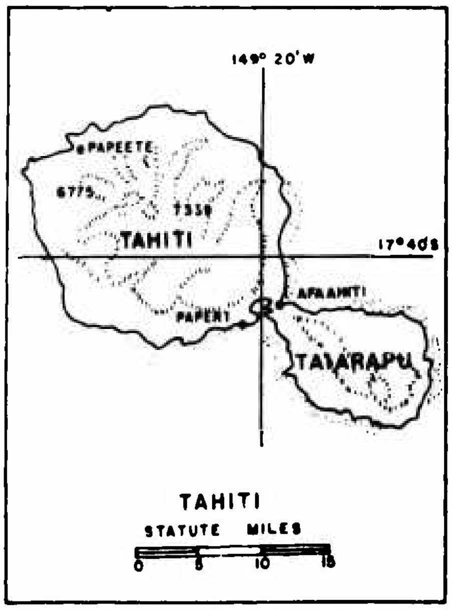

Fig. 3-11. The Geography of Tahiti.

It seems that orographic disturbances of the winds are only with difficulty separated from the land-sea breeze regime. There is always a tendency for a large eddy to form, in the vertical plane, in the lee of high mountain barriers in the tropics. Furthermore, the eddy is often detected at the surface as a foehn wind. In the afternoon temperatures are usually much higher on the lee plain and lee coast than on the windward side of the island. The combination of surface heating and upper level eddy circulation set up by the mountains produces the sea breeze. On some lee coasts this may become strong. For example, it is not unusual for the southwest sea breezes on the lee coast of New Caledonia to attain the speed of 25 knots in the face of the prevailing trade winds. Similarly, the land breeze at night

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is best developed on mountainous islands and is undoubtedly a combined land breeze -- mountain wind phenomenon.

In most cases, it is difficult to estimate the depth of the sea breeze circulation. On the few islands where a study of vertical structure has been made there seems to be a good correlation between the depth of the circulation and the height of the mountain barrier. At Batavia, Java, for example, the sea breeze circulation may extend to a depth of 8,000 feet during the middle of the day. On the other hand, at Nandi on the west coast of Viti Levu in the Fijian Islands the sea breeze and return-current system do not usually extend above 4,000 feet. The mountains on Java are much higher than those on Fiji and there is an approximate correlation between the depth of the sea breeze and the heights of the mountains windward of the station. The whole subject of land and sea breeze circulations is badly in need of investigation and it would pay the forecaster newly entering a region to spend a little time studying the details of the land and sea breeze regime of all important stations in his area. The literature usually contains studies of individual stations which may be taken as a guide. The analyst should study the lower layers of wind soundings from stations which lie in the lee of mountain chains or peaks and attempt through experience to correlate the lower level winds with the height of the obstacle and with the direction of the general wind over the ocean. In low level analysis, experience of this kind will enable him to extrapolate from the upper levels of the soundings, above the height of the mountain barrier, downward toward a reasonable representative wind for use in large-scale synoptic analysis. On the other hand, he must take the sea breeze into account in analyzing local weather and issuing local forecasts.

It has already been pointed out that heavy showers from cumulus congestus or from cumulonimbus are almost invariably accompanied by downdrafts. The effect of these drafts can often be seen by an observer flying in the neighborhood of a shower cloud over the open sea. In addition, to the rain pattern on the surface of the water, the so-called squall winds accompanying the shower and surrounding the cumulus cloud, particularly at its forward moving edge, can easily be seen on the surface of the water. In former times sailors used to report these as squalls, or rain squalls; indeed, to many seamen of the present day a tropical squall invariably means rain accompanied by strong gusts. Anemometers on atolls frequently show the marked correlation of this type of wind with the onset of a shower. While the general wind may be only 5 to 10 knots, immediately before the shower and during the early part of its passage, squalls or gusts to 40 knots or more may be experienced. Naturally, on an island like Guam (where these squalls are quite frequent in the wet season) the anticipation of sudden wind changes of this nature at air fields is a matter of some importance to successful forecasting. It is perhaps not so easily realized, however, that such squall winds also have to be considered during analysis. Observers, recording the surface wind, are usually well aware of the unrepresentative nature of the squall wind and will generally report a wind speed and direction that has been prevalent over some time; the squall winds are then reported as special phenomena. What is forgotten is that these squall winds may partly vitiate the value of a pilot balloon or rawinsonde observation. If the rawinsonde is released just before or during the passage of a shower, so that the lower transit of the balloon is in the region of downdraft, quite unrepresentative winds may be reported. All observations of winds at levels below 4,000 feet made during the period of heavy precipitation should be treated with caution.

4000. WIND ANALYSIS

4100. GENERAL REMARKS ON WIND ANALYSIS.

The quantities ordinarily arising from meteorological measurements and entering into their subsequent analysis belong to two classes called scalars and vectors, respectively. A scalar has magnitude but is not related to any definite direction in space; it is completely specified by a single number. For example, the mass of a body and the density of a gas are quantities which require for their specification only the assignment of a number which is obtained directly through observation or indirectly by calculation. On the other hand, a vector quantity requires for its complete specification not only the assignment of a number representing its magnitude but also a statement of its direction in space. The speed and direction of a body and the atmospheric pressure gradient at a point are examples of vector quantities. The true wind is a vector quantity, that is to say, in addition to magnitude it has a definite direction in space. At an instant the true wind may be oriented in any direction with respect to the vertical and horizontal axes through the point of observation and it will fluctuate widely from instant to instant. However, it is only the horizontal components of the true wind that are averaged durin the process of observation and it is this average horizontal wind with which we deal in synoptic meteorology. Vertical components are neither observed nor, under ordinary circumstances, computed. Each wind observation is usually referred to a point in a surface, parallel to or coincident with the surface of the earth, the height of the surface being specified. The wind vectors which are considered during wind analysis then lie wholly within this surface of reference.

The object of wind analysis is to construct a continuous representation of the wind field from the observations of the two-dimensional horizontal wind vectors on each surface. The various surfaces together constitute a complete analysis from which it should be possible to read the horizontal direction and speed of the wind at any point in the analyzed space.

The complete analysis of the wind field also provides a means of obtaining other subsidiary fields, such as the divergence and vorticity of the wind (refer to section 6200.). While work on the practical application of these derived fields has progressed very slowly and has not yet reached the stage of everyday operational use, we may assume that future work will lead to better understanding and greater use of them.

The difficulties of wind analysis arise both in interpolation and interpretation. First, interpolation is a much more difficult process than any customarily encountered in temperate zone weather stations where the interpolations practiced on a routine basis have been of the scalar type. The analysis of the pressure field, for example, is a relatively simple process; a scalar field of this type requires for its representation only one set of lines falling in simple patterns. A vector analysis, however, such as that of the wind field, involves a much more

difficult interpolation. The patterns are not simple; furthermore, they occur in two sets of lines which must be superimposed. The process of interpretation also, is more difficult. Behind the developed synoptic models of frontal analysis lie almost one hundred years of experience in the analysis of pressure fields; there are thousands of practitioners of the art, and in their daily work they continually check and improve the application of the models. In contrast, wind analysis is, as yet, rare outside the research laboratory. The relation of the wind analysis to other fields, such as that of pressure, is very obscure over a large part of the earth. Files of well-analyzed wind maps are rare and the complexity of the patterns displayed on them makes the statement of general rules very hazardous.

4200. REPRESENTATION OF THE WIND FIELD.

There are many possible representations, graphical and non-graphical, of vector fields. The choice of one for use in practical synoptic work depends upon several factors: the customary materials of the map analyst, the ease of comparison with other meteorological fields usually studied in weather stations, the method of observation, and the manner in which the observations are recorded and transmitted. As mentioned in section 3800., the winds which interest the synoptic meteorologist are time averages of the true wind over a period of the order of one minute and space averages over volumes of the order of one cubic mile. On the scale of maps used in most weather stations and on the time scale of the changes which have to be forecast, these winds may be referred to a point in space and to an instant in time without serious error. The place of observation is sufficiently well specified by plotting it as a point on a map bearing a latitude and longitude grid, and by a map reference to the height of the surface of analysis above sea level. If the map scale is such that a point can be located to the nearest tenth of a degree, both of latitude and longitude, all practical purposes will be served. Maps of a smaller scale are usually not sufficiently large to show the space variation of the observed winds, especially if calculations, such as those leading to a knowledge of the vertical motion, are intended to be made. Small-scale maps, however, are sometimes useful for preliminary sketches before the definitive analysis is attempted. In addition to the height of the analytic surface and the latitude and longitude grid, the map should specify the time of observation (to the nearest hour) or, in the case of a prognostic map, the time to which the prognosis refers. If the region of analysis includes land areas other than very small islands, it is a great advantage to have the representation of these land masses contoured at 1,000 foot intervals on the base map. It almost goes without saying that, for use in the tropics, the map must be of a Mercator's projection.

4210. The Two-Component Method.

Since only the horizontal components of the true wind are averaged in wind observations, they can be specified by plotting their component toward the north (this we shall call the v-component) and east (u-component) at the point of observation. Wind analysis can then consist of separate scalar analyses of

the u-field and the v-field, using interpolations similar to those on pressure or contour maps; the final result is derived by superimposing the two sets of lines so obtained, on the same map. Figure 4-1 is an example of this type of analysis. For certain computations, chiefly used in research work, this form of analysis is sometimes useful. However, for the development and application

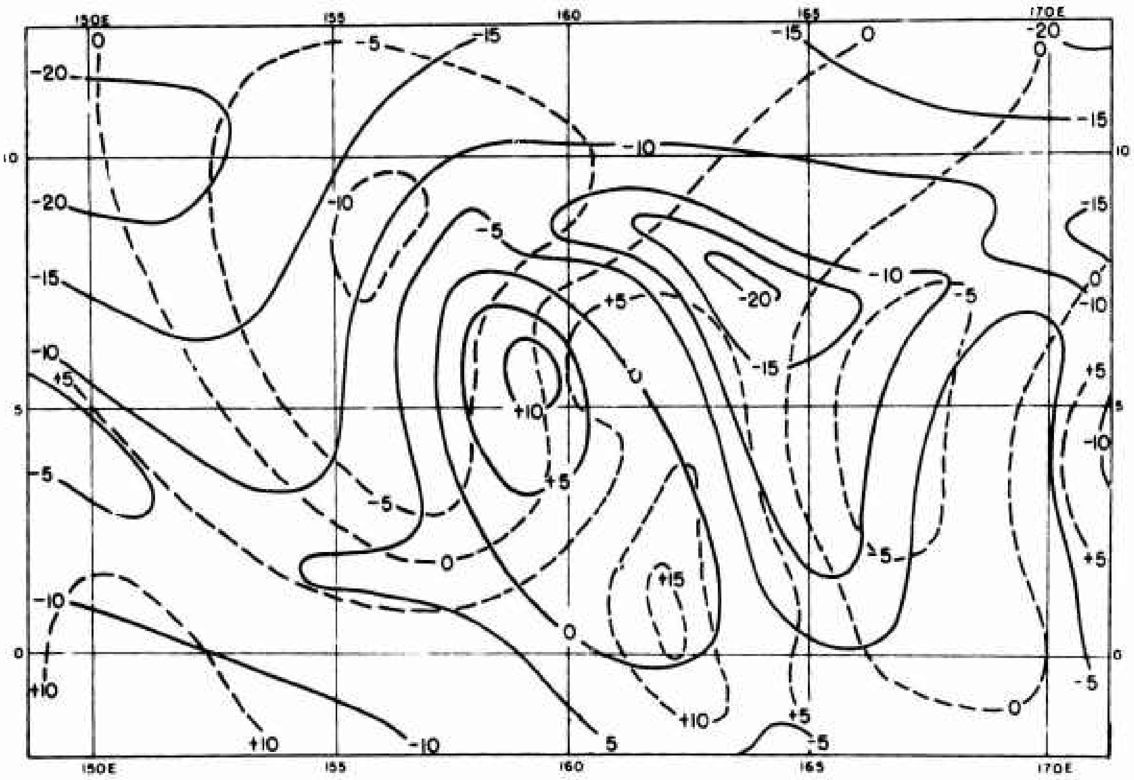


Fig. 4-1. The two-component method of wind analysis. The solid lines are East components. Broken lines are north components

of synoptic models, the loss of the intuitive picture of fluid movement, which we all possess as a result of everyday experience, is a serious handicap. Further, wind observations are not normally transmitted in the form of two components, so that a tedious resolution of the wind vectors is required before plotting. Obviously it is an advantage to plot the winds in the form in which they are received in the weather station and this imposes certain restrictions on the final representation of the wind field. At the present time winds are specified by the direction of the horizontal vector, measured in degrees clockwise from the standard direction of north, and the speed or intensity of the horizontal vector, measured in knots.

4220. The Vector-Arrow Method.

One of the simplest and most graphic methods of representing vector quantities is to plot them as arrows pointing in the direction of the vectors and of length proportional to their magnitude. There are great disadvantages to this method, however, when it is applied to wind analysis. To the eye, the longer arrows, representing high wind speed, assume the greatest importance. In regions of strong wind and dense observations, a net of overlapping arrows is obtained and it is not easy to see, at first glance, the individual points to which the observations refer. To achieve a complete analysis, the analyst must place interpolated vector-arrows at regular intervals between those that represent observed winds. Such an analysis is difficult to perform and, when completed, consists of a maze of arrows confusing

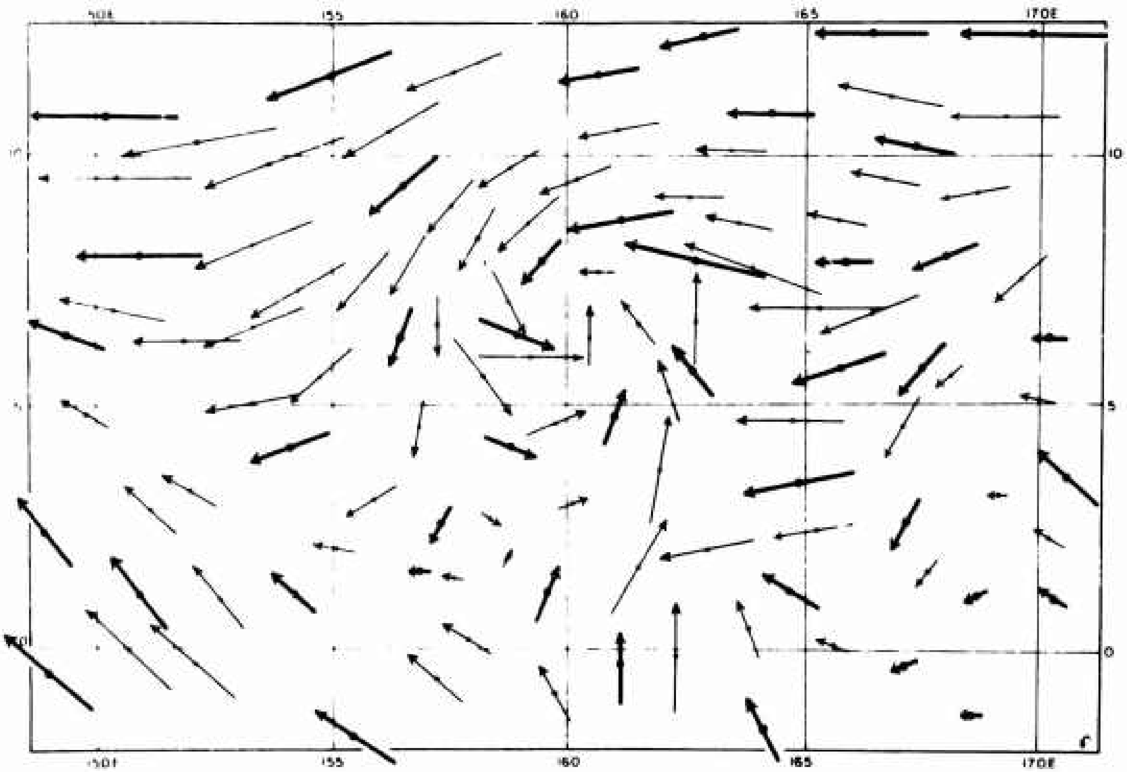
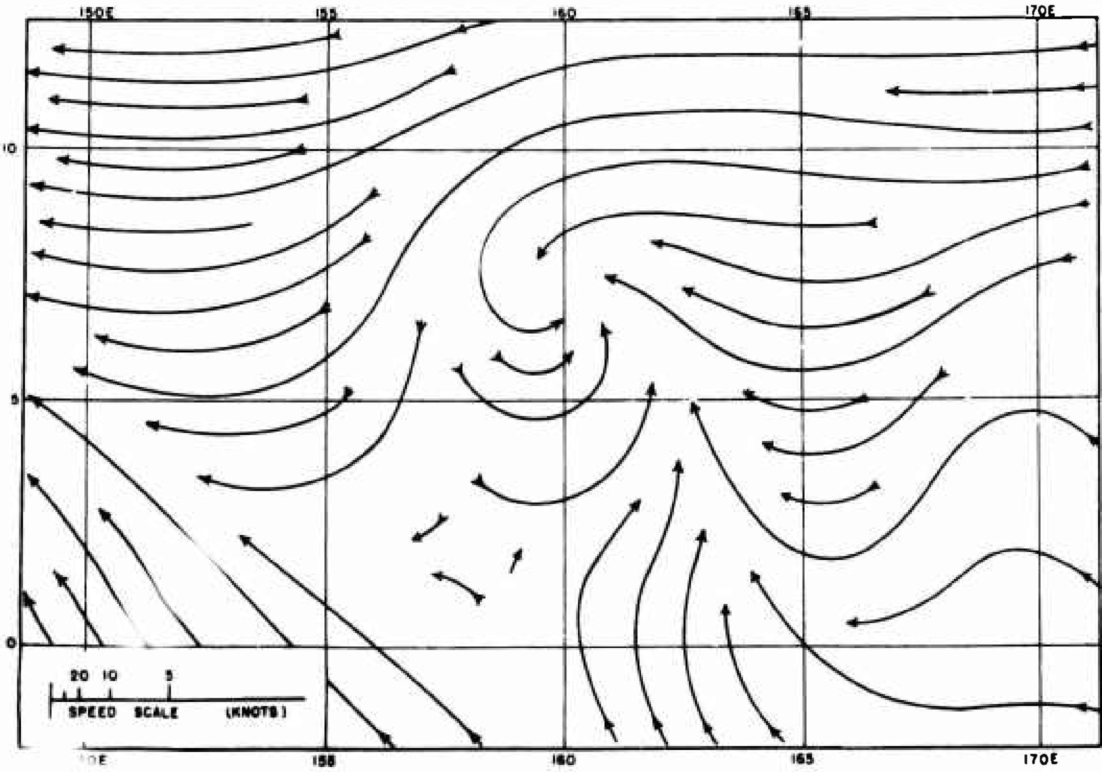


Fig. 4-2. The vector-arrow method of wind analysis. Heavy vectors are plotted data. Light vectors are interpolated

to the eye. Finally, the wind speed cannot be read from the analyzed chart. without the aid of a scale for measuring the length of the arrows. Figure 4-2 illustrates this type of wind analysis.

4230. The Discontinuous Streamline Method

This method involves a single set of lines drawn tangential to the winds and spaced according to an arbitrary speed scale. This, of course, means that in areas of speed convergence (see section 6200.) some lines must be dropped from the field and in areas of speed divergence lines must be added to the field; thus the streamlines are discontinuous. While this method has been used in the past, it is easily seen that it is impossible to represent completely the true horizontal wind field in this manner. For example, in areas of horizontal streamline convergence (see section 6200.) the streamlines must converge toward each other; yet the speed may be decreasing downstream rather than increasing, as the tighter spacing would indicate. Figure 4-3 illustrates this type of wind analysis.



Fi . *The discontinuous streamline method of wind analysis. Wind speed is indicated by the spacing of the streamlines.*

4240. The Streamline-Isotach Method.

The best form of wind analysis available at the present time consists of two sets of lines. The first set (called the streamlines and bearing arrowheads) is entirely devoted to representing the direction of the wind. The second set of lines, called the isotachs or isovels, represents the wind speed and is labeled in knots. A complete analysis consists of both sets of lines, one superimposed upon the other. If the lines are sufficiently close together, it is possible to read the wind direction from the streamlines and its speed from the isotachs

at any position on the map. An intuitive picture of fluid motion may be applied to this type of analysis and the wind data may be plotted directly from its transmitted form. Figure 4-4 illustrates a completed streamline-isotach chart.

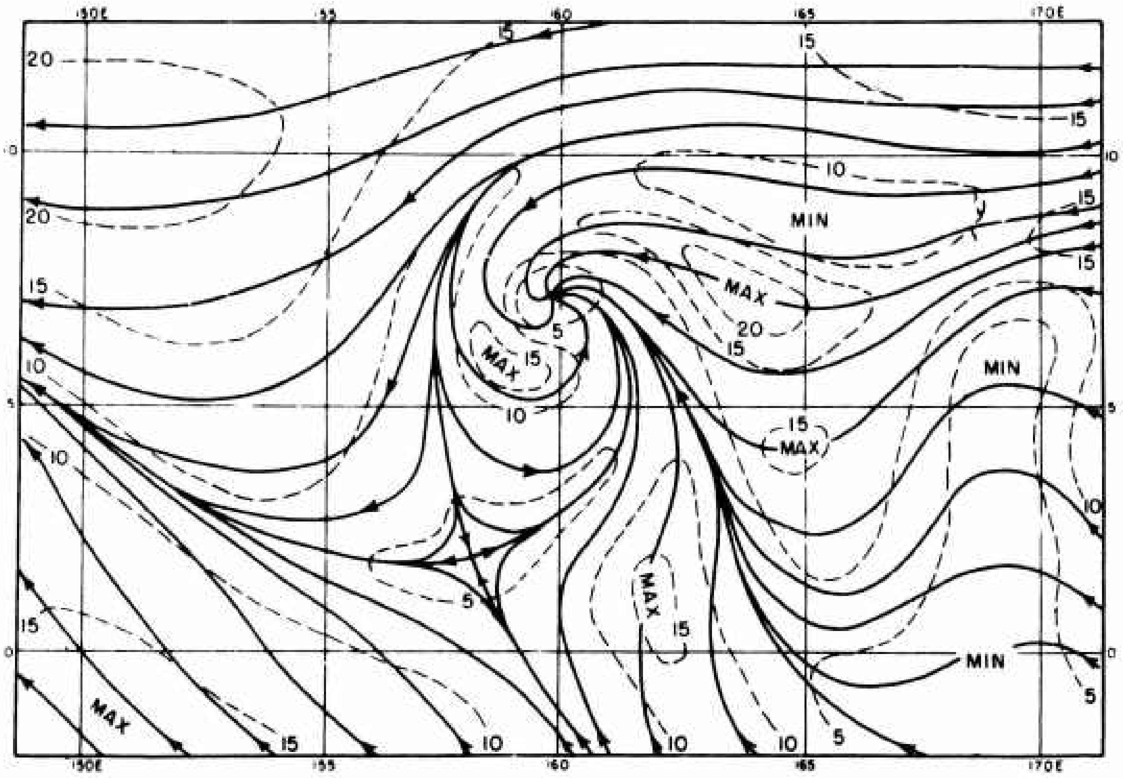


Fig 4-4. The streamline-isotach method of wind analysis. Streamlines represent only the wind direction. Isotachs represent the speed.

4300. SYNOPTIC WIND PATTERNS.

In the streamline-isotach method of wind analysis, as in other types of meteorological analysis, familiarity with standardized synoptic patterns is essential, especially in areas of sparse data. We are all familiar with the patterns found and followed in conventional sea-level pressure analysis, such as highs, lows, troughs, ridges, fronts, and wave-to-occlusion trains. In wind analysis the patterns identified at present are the "tropical currents", asymptotes, waves, singular points and speed maxima and minima. We will first discuss the streamline patterns, then the isotach patterns, and, finally, wind patterns in the vicinity of fronts and shear lines.

4310. Tropical Air Currents.

Tropical air currents cover the whole oceanic area between 20 to 25 degrees North Latitude and 15 to 20 degrees South Latitude. This area is subject to the well-known seasonal variations mentioned in section 2211. The currents are difficult to describe, since they have no well defined boundaries. However, they may be thought of as rivers of air often many hundreds of miles in length. They appear on the wind charts as bands of gently curving, relatively parallel,

streamlines. The composite streamline pattern, frequently appears to consist mainly of these broad currents which spiral outward from the major anticyclones, into zonal flow, i.e., tradewinds, and similar smaller currents which spiral into the low latitude cyclones. The correct interpretation of the movements and changes in these currents is often as essential to the analysis as that of the singular points (section 4340). Figure 4-5 illustrates this composite streamline pattern.

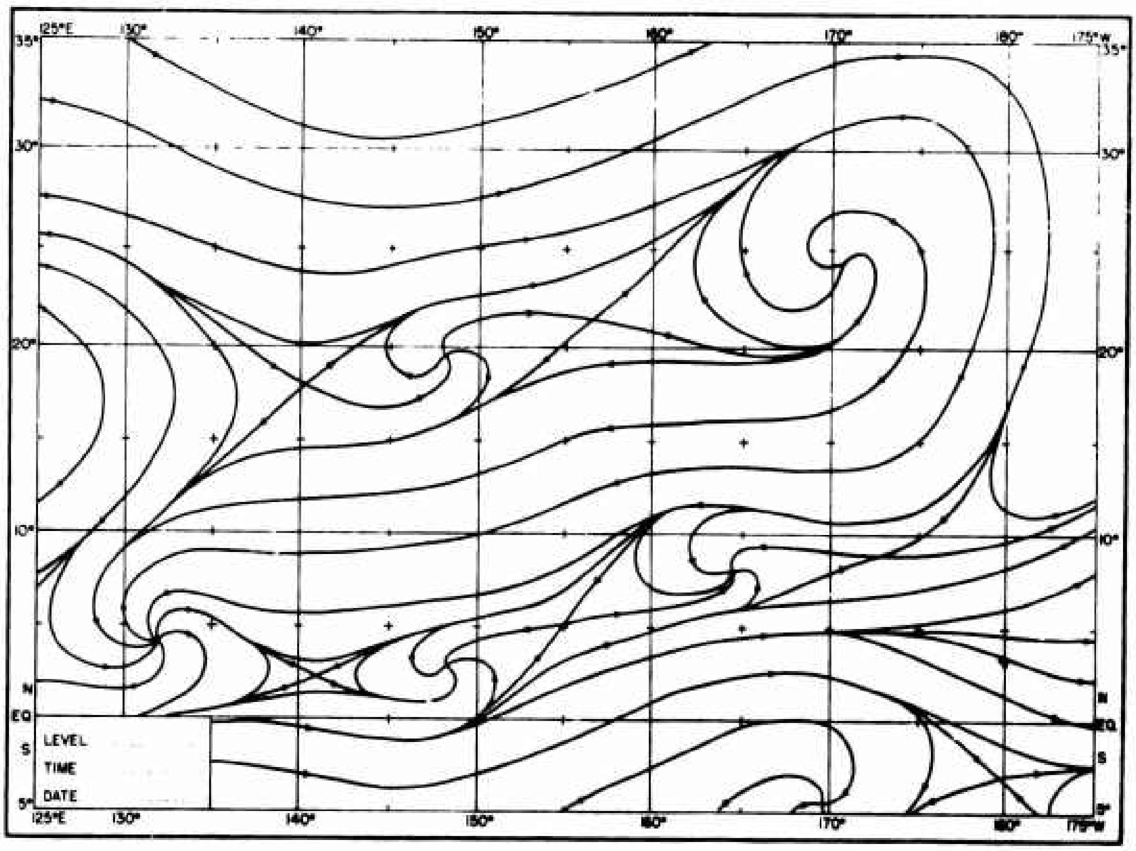


Fig. 4-5. Typical low level streamline pattern over a large oceanic area.

The trades and monsoons discussed in section 2200 represent the mean flow patterns produced statistically in the low levels by these currents.

The trades consist of numerous such currents which enter the tropics from the north or northeast in the Northern Hemisphere, and from the south or southeast in the Southern Hemisphere. These currents originate in mid-latitudes, enter the tropics around the eastern ends of the subtropical anticyclones, and continue westward through the tropics. Each individual anticyclone which is integrated into the subtropical band of high pressure, has associated with it one or more of these currents, which merge in the broad tradewind zone.

The term, "trades", applies strictly to the wind flow and must not be confused with the pressure pattern. The cross-isobar component of the wind is generally such that, at low latitudes; flow in the southwest side of the anticyclones remains easterly rather than southeasterly. When the equatorial trough is displaced well into the opposite hemisphere, these currents frequently cross the equator and recurve to become part of the monsoon currents.

The surface wind speed, in well-established, steady NE or NNE tradewind currents, is generally between 10 and 20 knots and at times reaches steady speeds of 25 knots or more. Over areas such as the Western Pacific where the tradewinds are more variable and frequently blow from the east or southeast the speed is generally less than 10 knots.

4320. Asymptotes.

Asymptotes form part of one of the simplest of streamline patterns. They may be defined as streamlines in the wind field away from which neighboring streamlines diverge (positive asymptotes) or towards which they converge (negative asymptotes). Theoretically, the asymptote would never be touched by the neighboring streamlines. Practically, because of the map scales commonly used, the asymptote has to be drawn as a streamline with which the neighboring streamlines merge (Fig. 4-6).

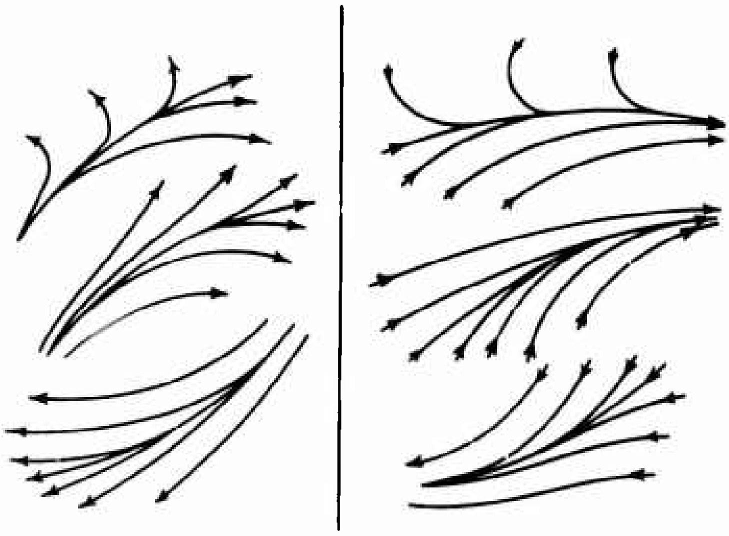


Fig. 4-6. Streamline asymptotes of divergence, left, and convergence right.

Identifying the asymptotes is one of the most important steps in streamline analysis; it enables the analyst to determine the main features of the overall streamline pattern. It must be remembered that the asymptotes may or may not represent lines of true horizontal mass divergence or convergence, depending upon the distribution of wind speed in the area. This is discussed in greater detail in section 6200.

4330. Waves.

Waves in the streamlines are merely perturbations in a wind current, analogous to the wave-like arrangement of troughs and ridges in isobaric patterns. The term "wave" is applied by some forecasters only to the cyclonic portion of the perturbation i.e., the trough, but this should be avoided. Waves usually appear in the broad zonal currents (described in

section 4310) such as the tropical easterlies; these major zonal currents usually have one or more waves superimposed upon them at any given time.

In most cases waves do not extend across the entire width of the current in which they are embedded. They are then known as "damped waves". In this case the streamlines on one or both sides of the current have smaller amplitude than those in which the wave is most pronounced, (See Figure 4-7).

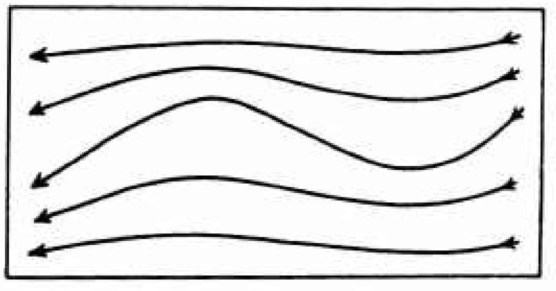


Fig. 4-7. A damped wave in the streamlines.

4340. Singular Points.

Singular points are the most complicated of all streamline patterns. They are points into which more than one streamline can be drawn or about which the streamlines form a closed curve. At these points the wind would appear to have more than one direction. This, of course, is impossible and we actually find no wind right at the singular point, i.e., there is zero wind, or a calm. Therefore, the winds in the neighborhood of a singular point are always relatively light, a useful fact when attempting to locate the singular points in the analysis. There are three classes of singular points, namely "cusps", "vortices" and "neutral points".

4341. The cusp is relatively unimportant in synoptic wind analysis since it is merely an intermediate pattern in the transition between a wave and a vortex and usually exists in any one plane for a very short period. Figure 4-8 illustrates two of the many variations of this class of singular points.

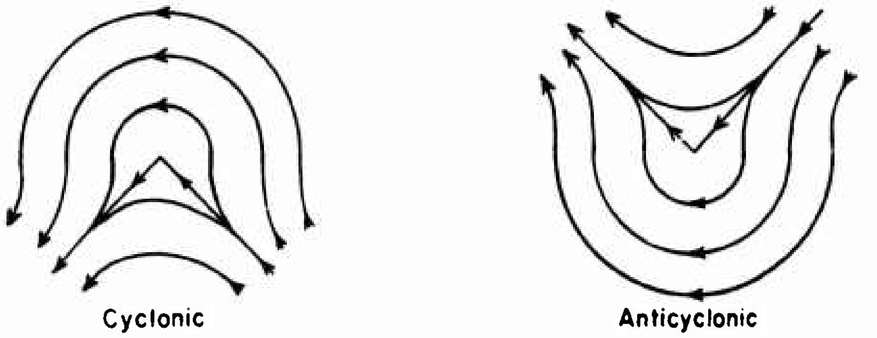


Fig. 4-8. Cusps in a straight east to west current.

4342. The vortex exists in great variety, accompanying outdrafts, indrafts, cyclonic flow, anticyclonic flow, and combinations of the first two with the latter two. Figure 4-9 illustrates the basic types of vortices generally found in the streamlines.

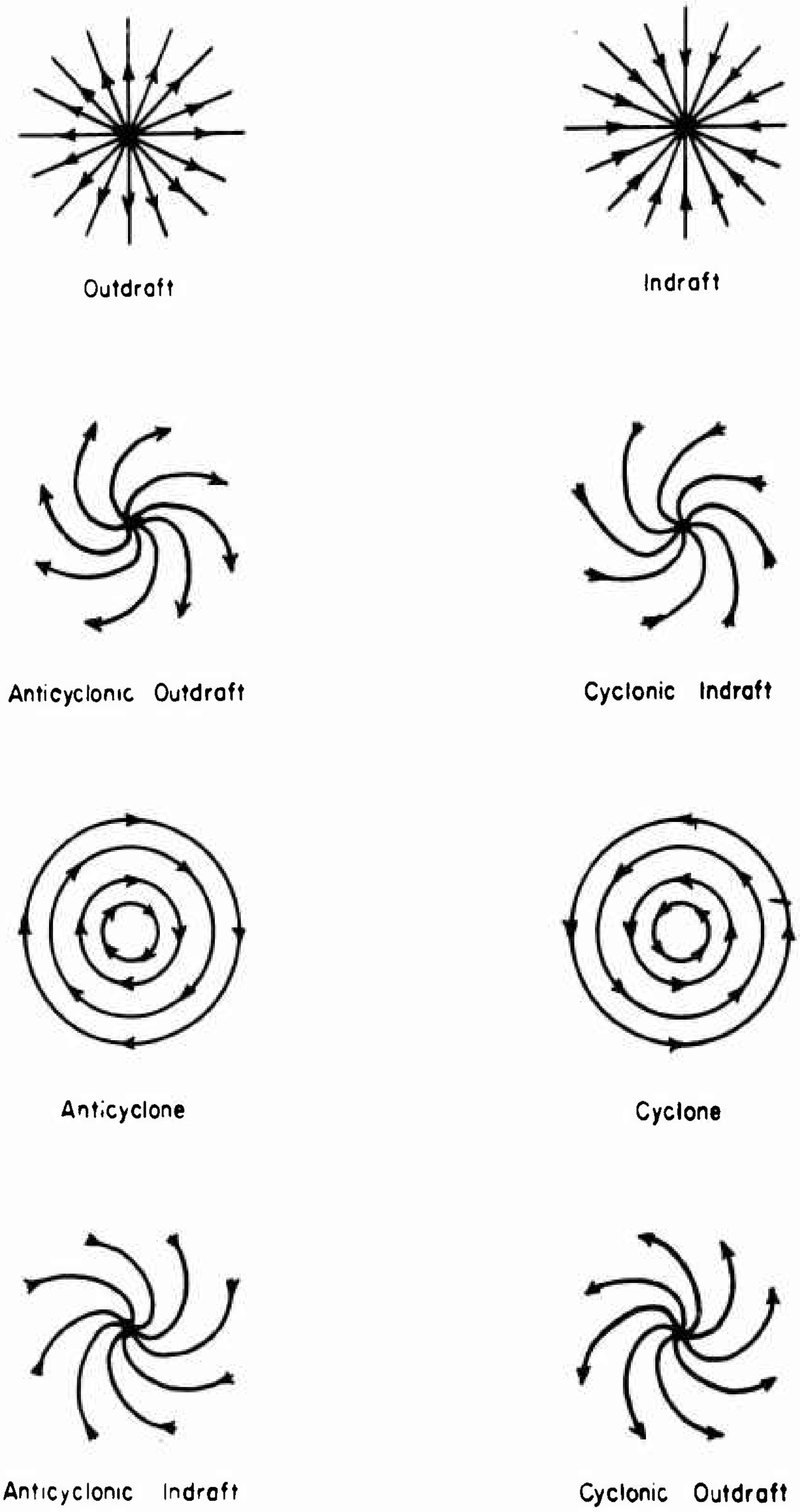


Fig. 4-9. Vortices in the streamlines. The cyclonic and anticyclonic classification applies to the Northern Hemisphere.

An outdraft represents the type of vortex from which the streamlines depart from the central point, in different directions. Naturally, streamlines rarely depart from a singular point in straight lines; they curve either cyclonically or anticyclonically. Thus, the cyclonic outdraft and the anticyclonic outdraft will tend to be more common than the "pure" outdraft.

The same is true of the indraft, where the streamlines come together from all directions. They, too, curve cyclonically or anticyclonically while approaching the singular point; thus, we have the cyclonic indraft and the anticyclonic indraft.

The experienced analyst will realize that, at low levels, the outdraft is most frequently combined with anticyclonic flow, while the indraft is most frequently combined with cyclonic flow. At upper levels, however, any of the combinations may appear. Pure cyclonic flow or anticyclonic flow may be relatively rare in nature; at least it is seldom observed at low levels. Unfortunately, at upper levels, the data are usually too sparse to determine the outdraft or indraft characteristics of the vortices. Therefore, many vortices at upper levels must be drawn as pure cyclones or anticyclones for lack of more detailed information.

4343. Neutral Points are those points at which two asymptotes, one of directional convergence and one of directional divergence, appear to intersect. They are analogous to "cols" in the pressure field in that they represent a "saddle" between two areas of anticyclonic flow and two areas of cyclonic flow. Figure 4-10 illustrates the typical streamline patterns in the vicinity of neutral points.

4344. The Transition from a Wave to a Vortex is frequently observed in the time continuity between successive streamline charts. This transition takes place during the amplification of the wave, which continues until a cusp point is formed in the streamlines near the center of the wave. The cusp point stage may appear on one of the maps in a series but has such a short life history that in most cases it develops between two successive synoptic maps and is seldom seen. Following the cusp point stage a vortex and a neutral point appear simultaneously as a pair. Then, as the vortex continues to grow, the neutral point moves away from the vortex center but always remains at the outer limit of the circulation around the vortex.

This transition may take place in either the cyclonic (trough) or anticyclonic (ridge) portion of the wave but is observed more frequently in the cyclonic portion. Figure 4-11 illustrates this transition.

The orientation of a vortex and a neutral point, which have formed from a wave in a major zonal current, follows a systematic pattern during the early stages of development. The direction of the neutral point from the vortex, relative to the line of motion of the system is determined by the characteristics of the vortex (indraft, outdraft, cyclonic or anticyclonic), as long as the current in which it is developing is approximately uniform in direction and speed, e.g the equatorial easterlies or the monsoon current. The distance between the two is dependent upon the

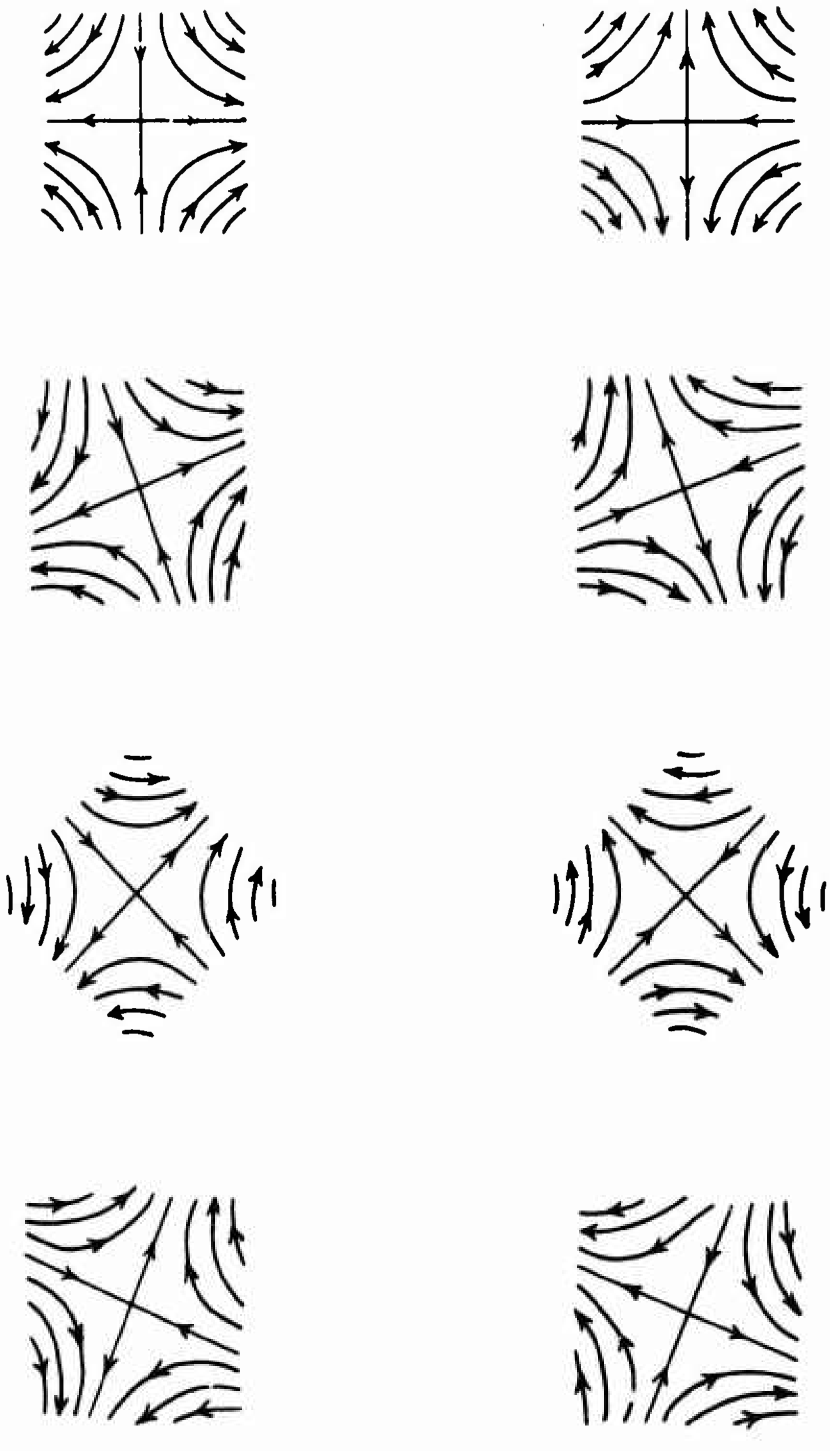


Fig. 4-10. Neutral points in the streamlines.

intensity of the vortex a feature difficult to judge in the early stages, the probable direction, from the vortex, in which the neutral point will lie, however, is more easily obtained.

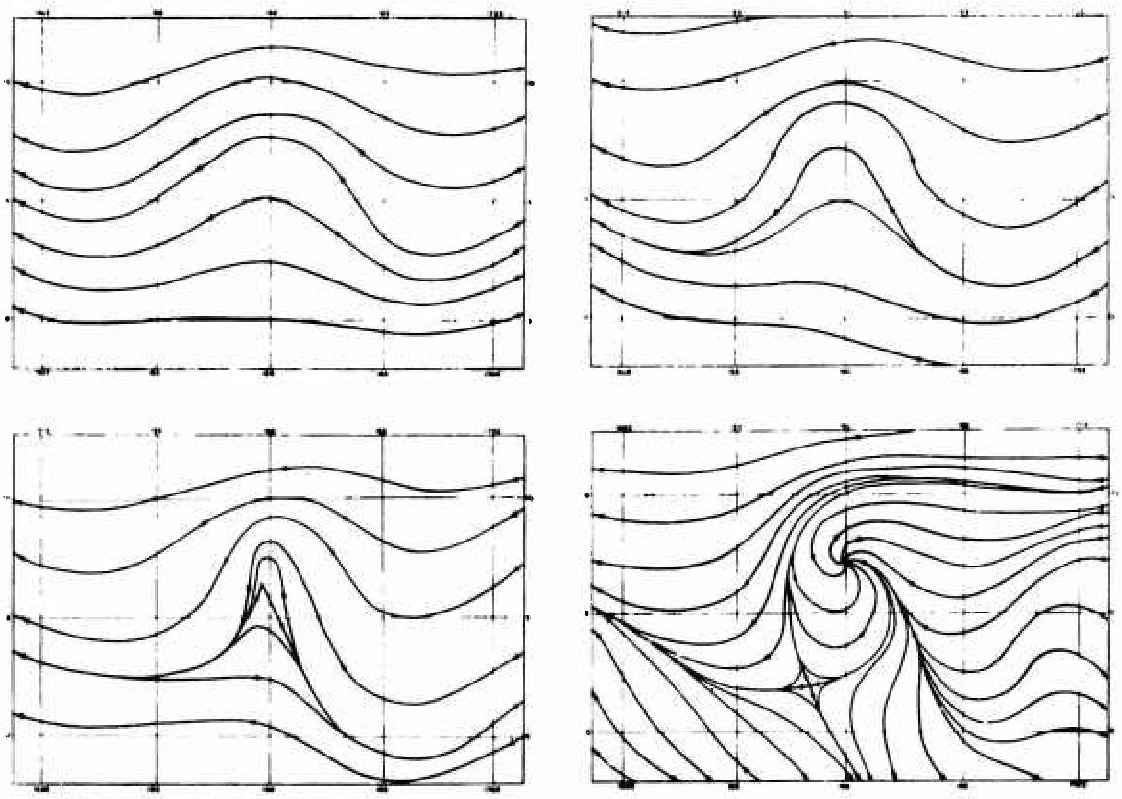


Fig. 4-11. The transition from a wave to a vortex-neutral-point pair through the cusp-point stage.

Looking downstream along the current in which the vortex-neutral point pair are embedded, in the Northern Hemisphere, we find that a pure indraft will have the neutral point directly ahead of it and a pure outdraft will have the neutral point directly behind it. Also, a pure cyclone will have the neutral point to the left and a pure anticyclone will have the neutral point to the right. Thus, a cyclonic indraft will have the neutral point in the left front quadrant and an anticyclonic outdraft will have the neutral point in the right rear quadrant (Fig. 4-12). Of course, in the Southern Hemisphere the neutral point will be to the right of a cyclone and to the left of an anticyclone. Again it must be emphasized that these relationships hold true only as long as both the vortex and the neutral point remain embedded in a current that can be treated as approximately uniform.

4350. Isotach Patterns.

Isotach patterns resemble those found in the simple scalar analysis of pressure or temperature, i.e., there are centers of maximum and minimum values and saddles or cols in the field. The cols, however, are usually poorly defined and difficult to locate accurately.

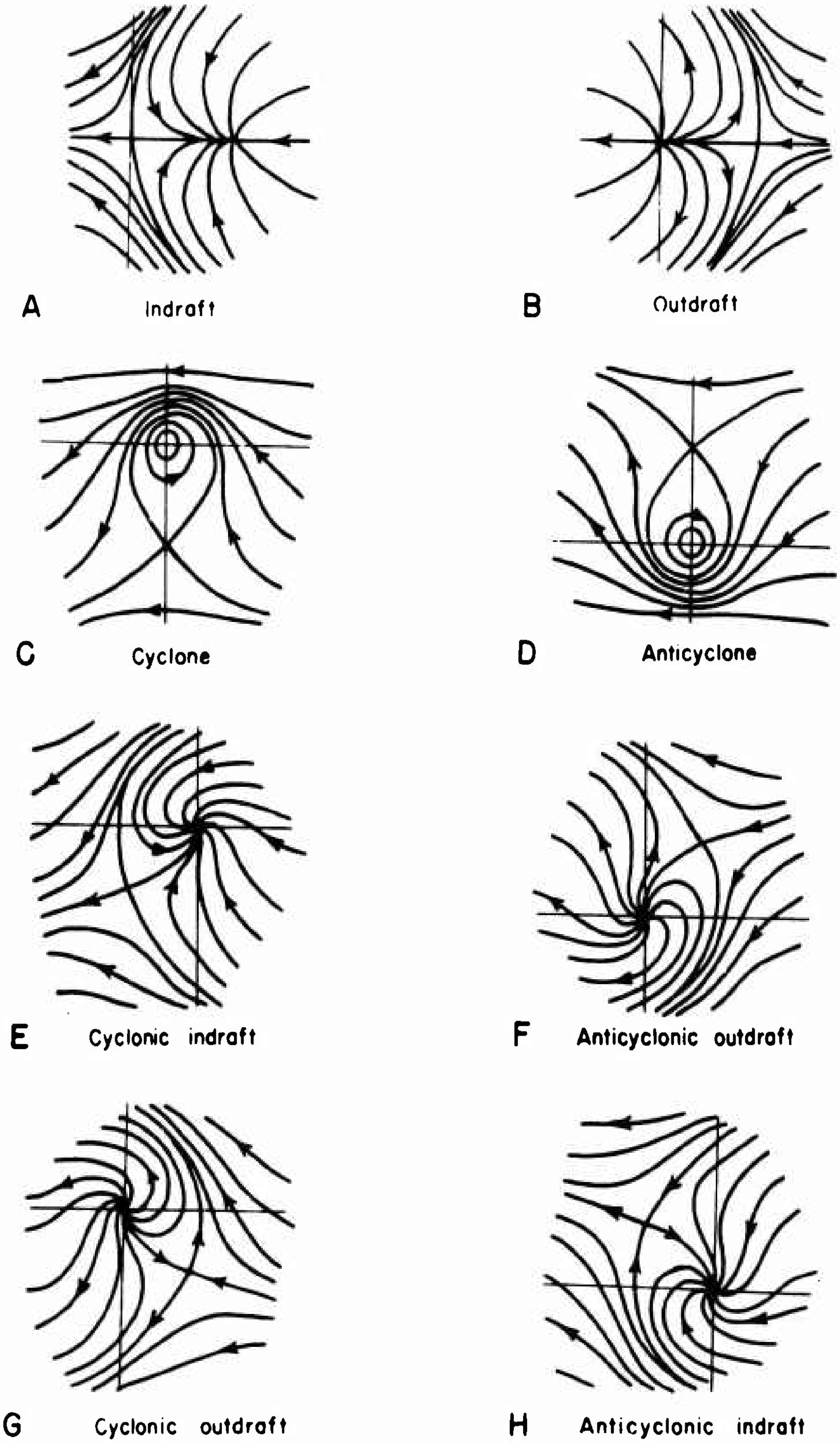


Fig. 4-12. Orientation of the vortex and its associated neutral point in an easterly current in the Northern Hemisphere.

The centers of maximum wind speed are usually greatly elongated, and the isotach spacing is usually much tighter on either side of these elongated speed maxima than it is along the major axes of the closed isotachs (Fig. 4-13). While little more can be said about identifiable patterns in the

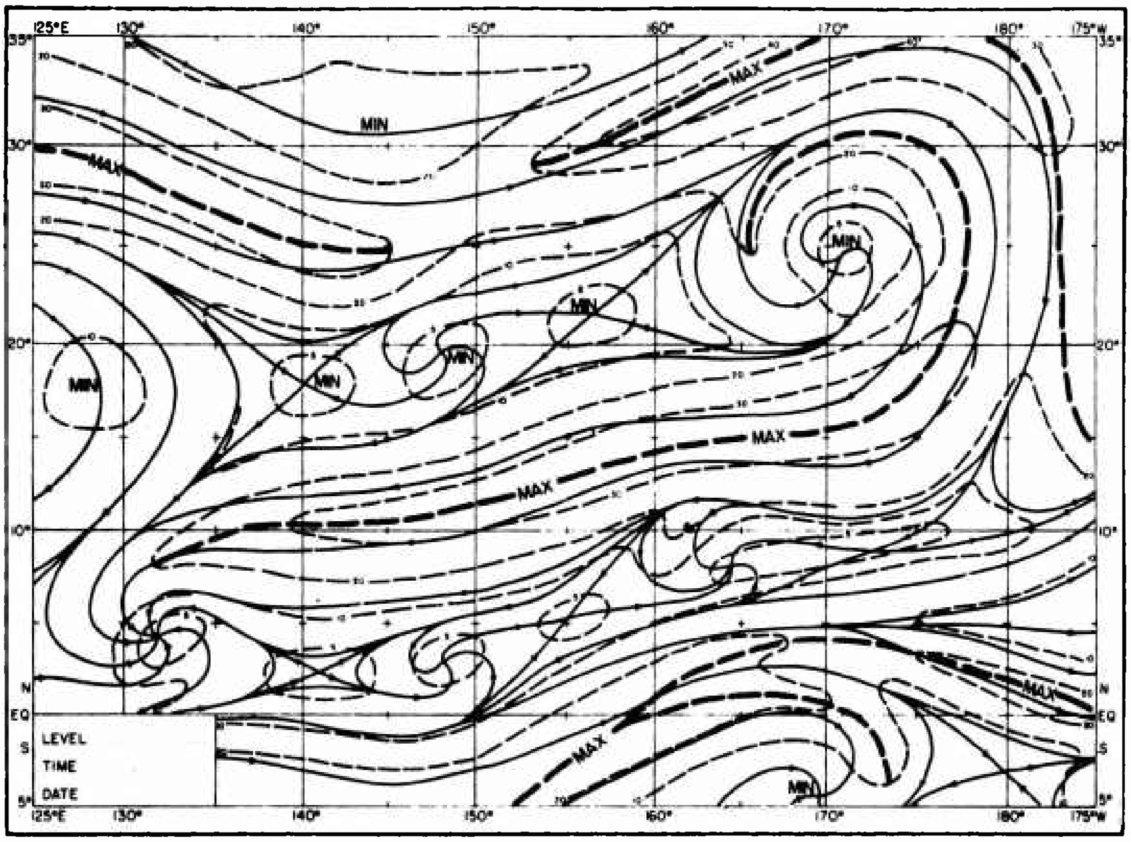


Fig. 4-13. Isotach patterns associated with typical streamline patterns over a large oceanic area.

isotachs, as such, certain typical relationships are believed to exist between the patterns in the isotachs and those in the streamlines. These relationships are presented here as an aid to analysis in areas of sparse data.

(1) The major axis of an elongated speed maximum usually lies roughly parallel to the streamlines, particularly in the major zonal wind currents e.g the N.E. trades. (See the heavy broken lines in figure 4-13).

(2) It follows that the isotachs on either side of elongated speed maximum are also roughly parallel to the streamlines.

(3) There is usually an elongated speed maximum located near the center line or core of each streamline current.

(4) Maximum wind speeds are usually greater in the major streamline currents, such as the tradewinds or westerlies, than in smaller detached currents.

(5) Within the major currents, points of maximum wind speed tend to occur where curvature in the current is slight (points labeled "MAX" in Fig. 4-13).

(6) There may be two or more elongated speed maxima lying side by side, roughly parallel to each other, within very broad streamline currents.

(7) A speed minimum always exists at every singular point in the field, since, by definition, the speed is always zero at these points.

(8) Speed minima which are not located at singular points will have values greater than zero at the center.

(9) Speeds are generally relatively light in areas of very sharp curvature in the streamlines, such as at the crest of the cyclonic or anticyclonic portion of a wave.

(10) When singular points are arranged in a closely spaced chain the speed minima associated with the individual singular points are usually connected by a band of relatively light winds. (Fig. 4-13)

(11) Winds will often be relatively light on a particular chart in an area where a singular point exists at the level above or below, or in an area where a singular point has just disappeared or where one is in the process of forming at the level being analyzed.

(12) Speed minima tend to be elongated along the asymptotes which lie between diverging or converging currents.

(13) It has been mathematically established that the isotachs in the immediate vicinity of neutral points should approximate ellipses. However, in this area of light winds the pattern in the isotachs is difficult to determine. Experience has shown that, as one departs farther from the neutral point, the ellipse in the isotachs tends to assume the form of a four-pointed star with the points of the star lying over the asymptotes which intersect in the neutral point (Fig. 4-14).

4360. Fronts in the Wind Field.

The relationship of fronts to wind patterns must be considered here because, while fronts are rare in the tropics, the polar front may, at times, move into very low latitudes. This occurs most frequently where the continents extend from middle latitudes to within a few degrees of the equator. The "friagems"

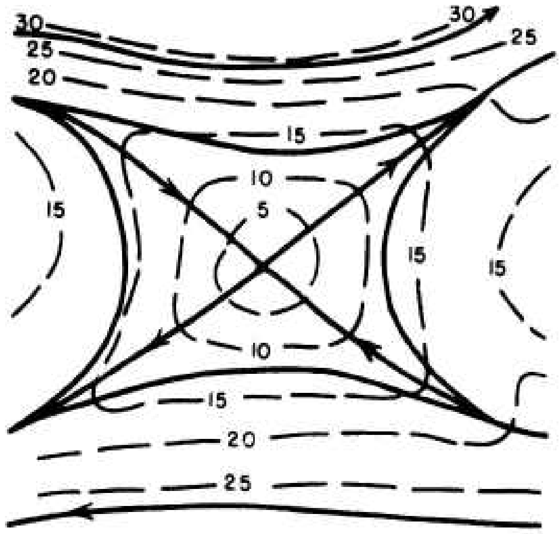


Fig. 4-14. Suggested isotach patterns around a neutral point.

of South America and the "northers" of Central America exemplify this situation.

In the areas where the front still maintains its characteristics as a density discontinuity and a line of cyclonic shear in the wind, it may or may not be treated as a discontinuity in the wind field depending upon the scale of the map and the conventions used in the analysis. The thickness or width of fronts is said to vary from three to sixty or more miles. However, by the time a front enters the tropics it is likely to be a frontal zone 30 miles or more in width. On the scale of most weather charts a distance of thirty nautical miles (½ degree of latitude) can easily be measured. Thus the front can be drawn as a narrow zone between two parallel lines, with the continuous pattern of the streamlines and isotachs clearly indicated (Fig. 4-15). If however, the convention of drawing the

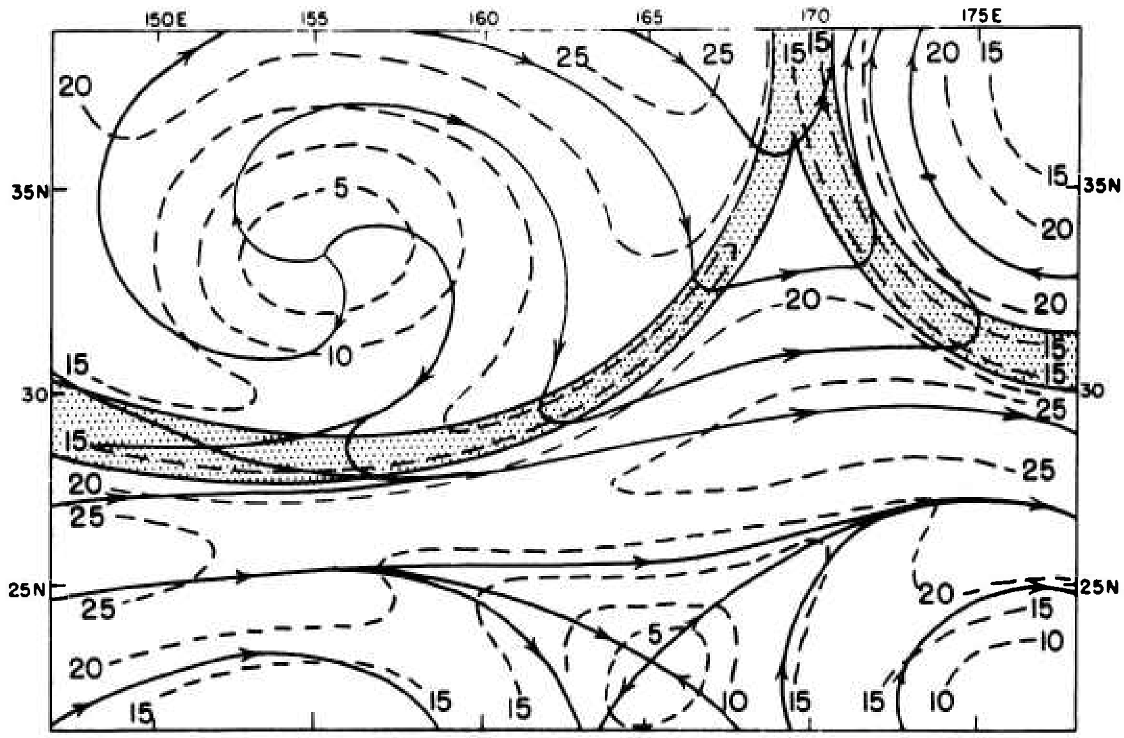


Fig. 4-15. Detailed frontal analysis in the wind field.

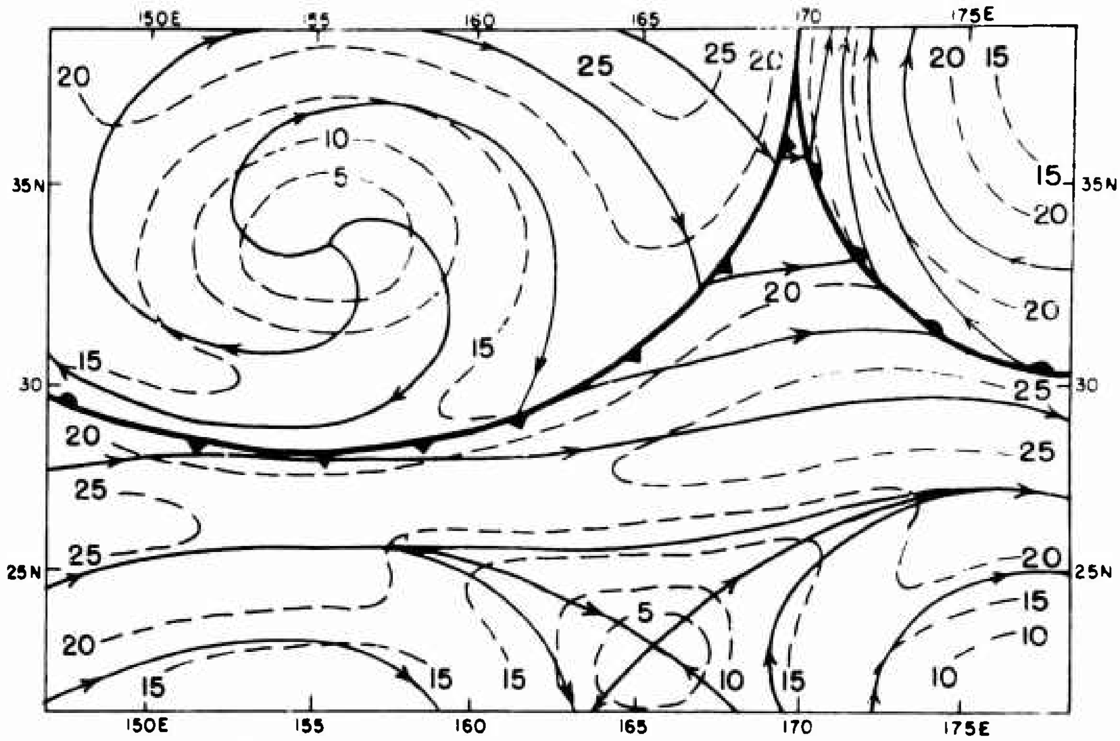


Fig. 4-16. Conventional frontal analysis in the wind field.

front as a single line is preserved, the streamlines and isotachs may appear t(break at the front (Fig. 4-16).

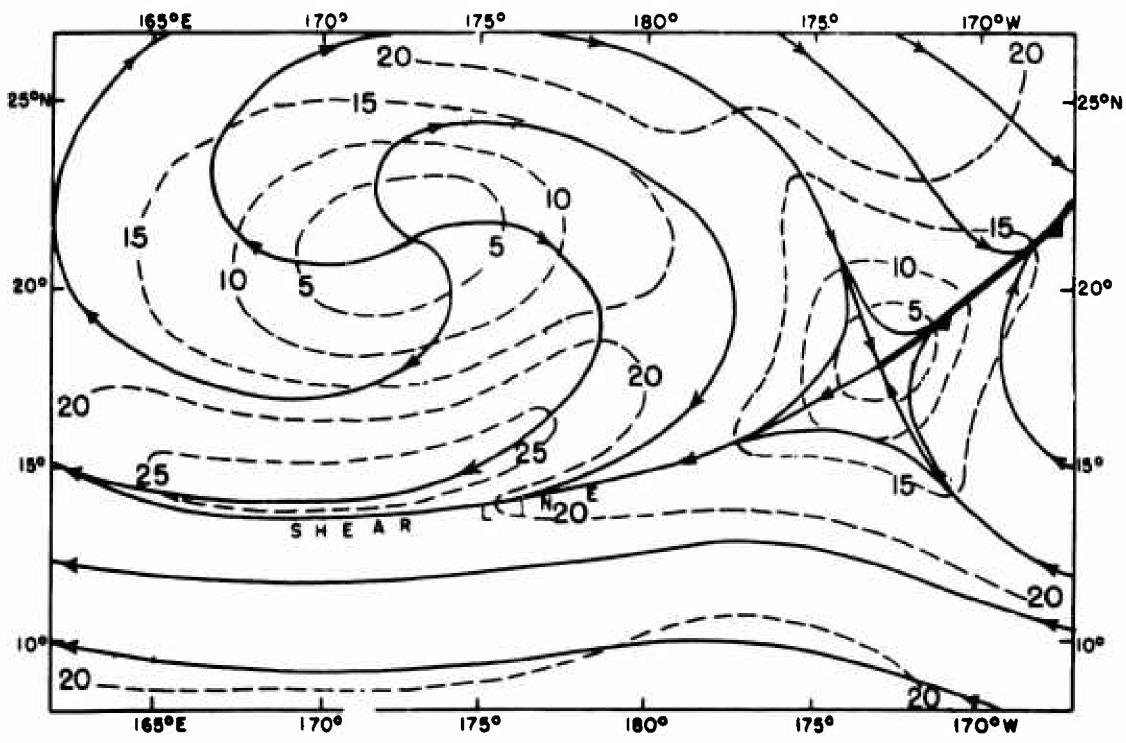


Fig. 4-17. A shear line in the wind field.

When the polar front approaches the tropics the cold air mass behind it is modified by passage over a warm uniform surface and by subsidence aloft and eventually the density discontinuity is dissolved, leaving only a belt or line of cyclonic shear in the wind (Fig. 4-17). This shear line may persist for several days and often continues to move very slowly equatorward, much in the manner of a front. The low level winds may be much stronger on the poleward side of the shear line than on the equatorward side. Therefore, its location is important to analysis and forecasting of the wind speed field.

4400. OPERATIONAL PROCEDURES.

In establishing procedures for analyzing the wind field, the factors to be considered are: the purpose for which the analysis is prepared, the amount and type of data available, and the number of man hours required by the analysis. The process of analyzing the wind field can be conveniently separated into the following steps;

(1) Determining the area to be analyzed.

(2) Selecting the levels to be analyzed.

(3) Plotting the data.

(4) Analyzing the streamline field.

(5) Analyzing the speed field.

(6) Completing the wind chart.

Analyzing the auxiliary charts can be placed between steps (2) and (3). However, it is more convenient to discuss the analysis of these charts along with the description of the charts themselves in section 4600.

4410. Determining the Area to be Analyzed.

The availability of data and the use to be made of the analysis determine the area to be covered. Other factors also must be considered. Middle latitude analysis of the subtropical anticyclones and of disturbances which may be approaching from higher latitudes cannot be neglected in any operational area near the 20th parallel. It is also wise to extend most analyses 10 to 20 degrees of latitude on either side of the equator because tropical cyclones in one hemisphere sometimes affect the weather in the other hemisphere.

4420. Selecting the Levels to be Analyzed.

The levels to be analyzed are also dependent upon the data and the purpose for which the analysis is prepared. The latter criterion is ignored too frequently. The custom of carrying out upper air analysis only for the standard pressure surfaces (850 mb, 700 mb, 500 mb, etc.) has become well established, even in weather stations which seldom issue a forecast for any of these levels but do issue numerous wind forecasts for flights at other levels. In the tropics it is more practical to work with the levels for which the most forecasts are required. When the analysis is tied into

a higher-latitude contour analysis the levels need not, for practical purposes, coincide exactly. For example, a station which most frequently issues forecasts for flights at 8000 feet should analyze the 8000 foot wind chart in tropical areas, and this analysis can often be joined to the 700 mb contour analysis for higher latitudes without introducing any great inconsistency. However, the latitude at which the two types of analyses join should be selected on the basis of the synoptic situation rather than an arbitrarily predetermined line.

Even in cases where little direct use will be made of a low level chart, it is advisable to begin the analysis with a chart for the lowest level at which the winds are reasonably free from orographic effects. Over the oceans any level between 1,000 and 3,000 feet is suitable. This allows full use to be made of the comparatively numerous low-level data. To establish vertical continuity successive upper level charts can be laid over the low level analysis.

The sea level pressure field can also be used to help complete the low level wind analysis. Singular points in the wind field are generally associated with centers of high and low pressure or cols though they may not exactly coincide. Major asymptotes of convergence are frequently associated with troughs in the pressure field.

Another reason for commencing the analysis at low levels is that the wind patterns at levels below 10,000 feet are most likely to be associated with the distribution of cumuliform clouds and their resulting weather (see section 6300.) and this association can aid the analyst in locating centers or lines of convergence in the wind.

If the analysis extends to a level about 10,000 feet above the actual level of interest, the forecaster obtains a better picture of upper disturbances; these may have an effect on the lower winds, that will be obscure at the given level, but which becomes obvious when the upper map is overlaid on the light table.

4430. Plotting the Data.

It is advisable to plot the wind direction with an arrow which extends an equal distance on either side of the station circle; there is a natural tendency to draw the streamlines tangential to the arrow at its midpoint rather than at one end. The arrow should be plotted with the aid of a protractor because sufficient accuracy can seldom be maintained when plotting free hand. Both the direction and speed of the wind should also be plotted in figures. This provides a check on the plotted wind arrow, facilitates isogon analysis and preserves the full accuracy of the coded wind speed.

Figure 4-18 illustrates a plotting model which has been found to serve these purposes accurately and easily. A time group is inserted in those cases where the observations are not taken at the synoptic hour already represented on the map. For example, it is impossible to get more than one observation which exactly corresponds to map time from a single aircraft. However, observations one to three hours off time are always useful, and methods of using off-time winds in the analysis are described later in this section. Similar remarks apply to off-level winds. If the wind shows little shear with height or is varying in a smooth manner, it is sometimes possible

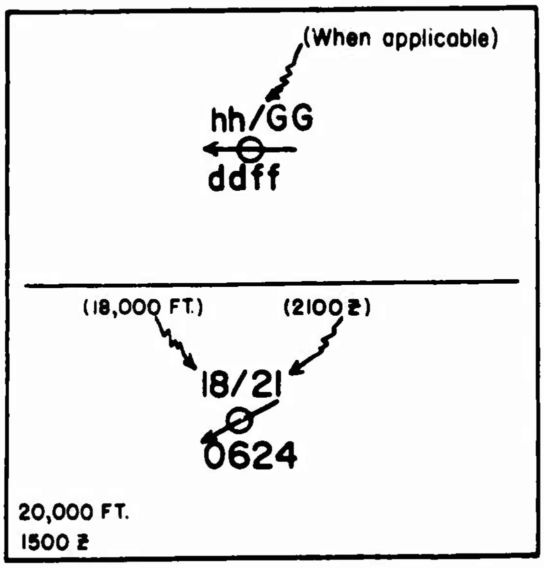


Fig 4-1B. A wind plotting model suitable for use with either the direct or the isogon method of drawing the streamlines.

to use a wind observed at a level just below the surface of analysis. For example, on a 10,000 foot analysis, those pilot balloons which reach only 9,000 feet often provide some useful information. The 9,000 foot winds should be plotted on the 10,000 foot map, and the fact that they are off-level should be clearly indicated; allowance has been made for this in the plotting model.

Strictly speaking, only winds of comparable accuracy should be plotted and analysed on a single map. For example, winds obtained by pilot balloon, rawinsonde, and double drift (by aircraft) can be plotted on the same map. But in the weather station other winds are received which, while they are not strictly comparable to those mentioned above are nevertheless useful checks upon the streamline analysis. The commonest winds of this class are those received from transient aircraft: the "navigation winds" obtained by the use of loran, celestial or radar fixes or dead reckoning. The volume over which the averaging process is carried out to obtain these winds may be many thousands of cubic miles in extent. Consequently, it is an error, even on the scale of the maps discussed here, to refer them to a point on the surface of analysis: they are essentially winds averaged over a very long track (usually over an hour's duration of flight). If such winds are to be used to check the streamline analysis, their character as navigation winds should be clearly obvious to the analyst. They may be plotted at a point, usually half-way between the position at the time of the report and that of the previous report, but they should be plotted in a conspicuously different manner from the more accurate winds.

In areas of sparse data the direction of motion of clouds may be the only clue to the direction of the upper wind. Therefore, the cloud directions should be plotted on the wind chart for the level nearest the cloud height. Low cloud directions should be plotted on charts for levels below 10,000 feet. Middle cloud directions are helpful on charts for levels between 10,000 feet and 25,000 feet. High cloud directions may be used for levels between 30,000 feet and 50,000 feet. Cloud directions should also be plotted in a distinctive manner to prevent their being mistaken for more accurate data. The exact height of clouds is not usually known and the directions are reported on an eight point scale. Therefore, they must be carefully evaluated by the forecaster and, at best, used only as a rough guide.

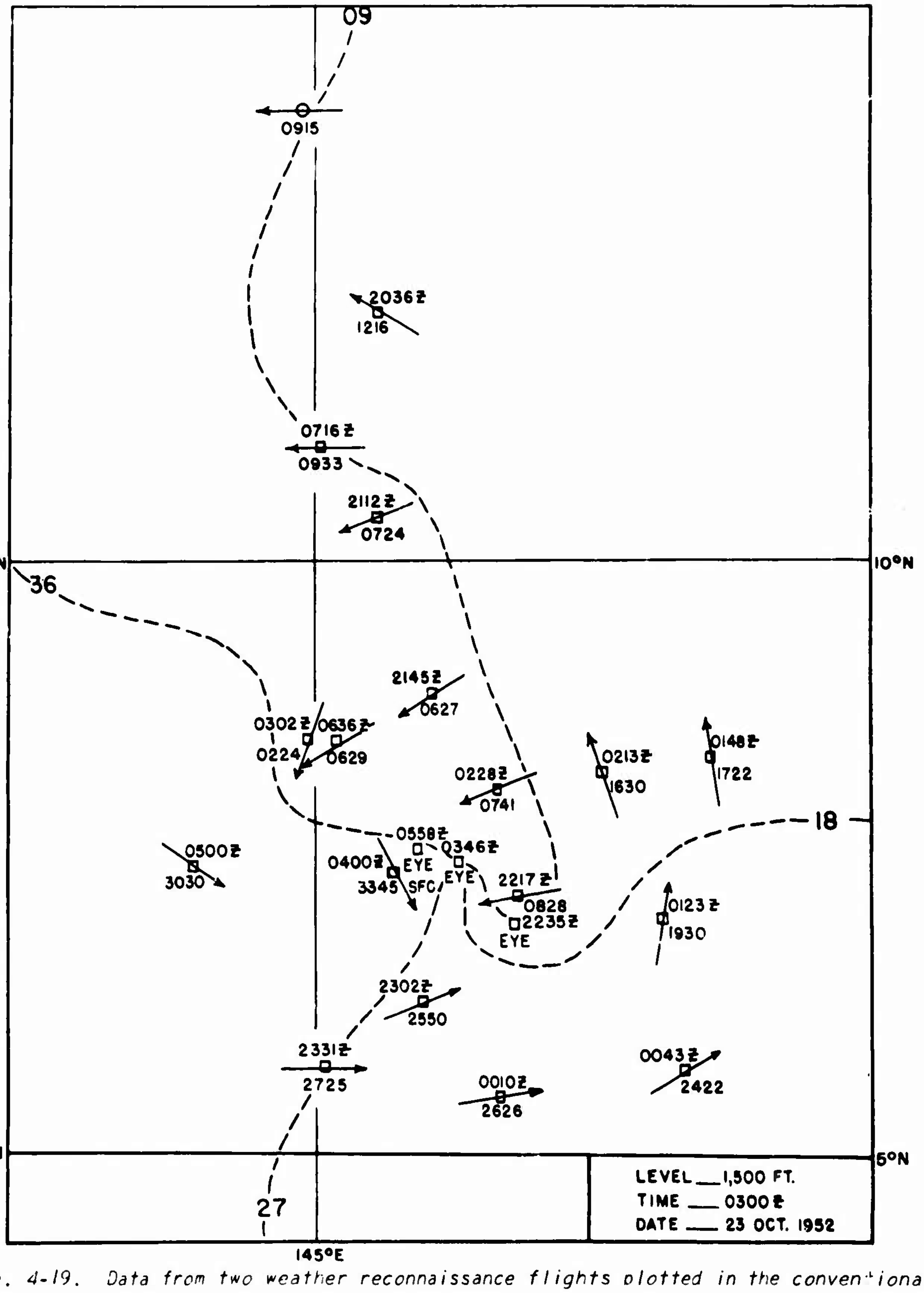


Fig. 4-19. Data from two weather reconnaissance flights plotted in the conventional manner.

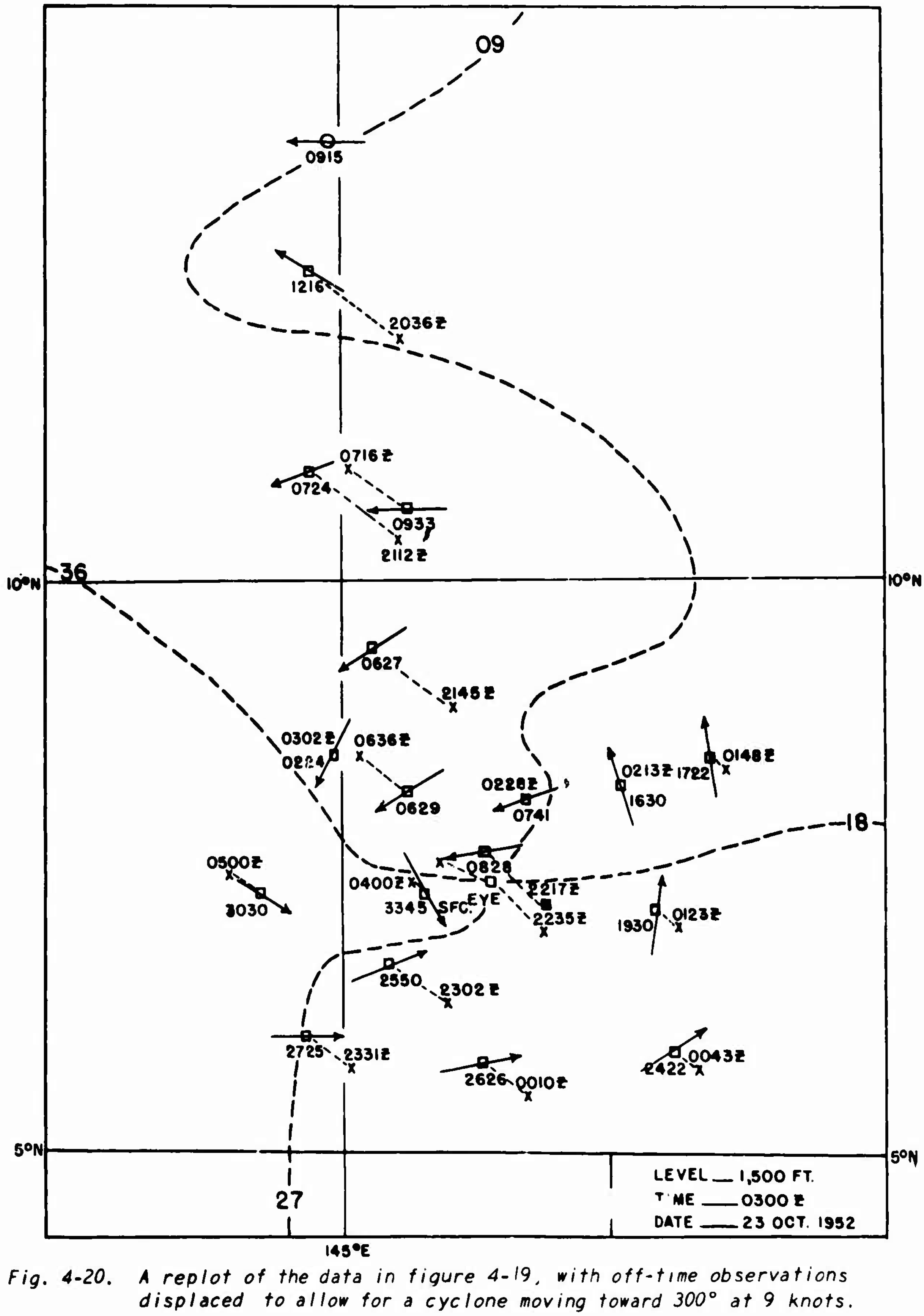


Fig. 4-20. A replot of the data in figure 4-19, with off-time observations displaced to allow for a cyclone moving toward 300° at 9 knots.

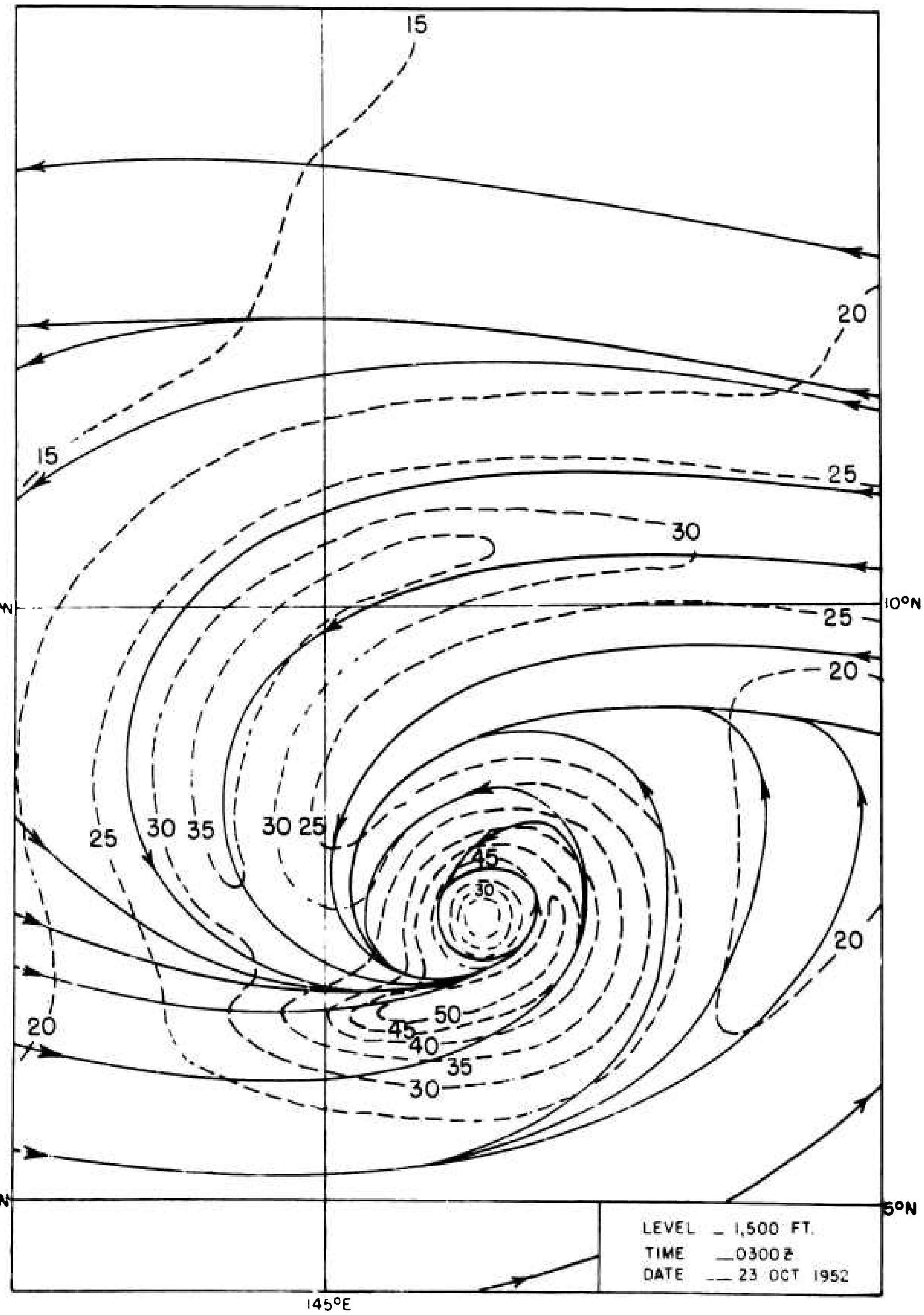


Fig. 4-21. An analysis of the replotted data in figure 4-25.

Surface winds reported from ships and flat low-lying islands are also useful on the low-level wind chart. The winds below 3,000 feet, in the tropics, generally vary in direction only slightly with height. Therefore, in the absence of marked orographic effects the surface wind directions may be used as a rough guide in analyzing the winds below 3,000 feet. The speeds, reported, however, must be used with very great caution.

If all off-time data are plotted in pencil or with diluted ink, the analyst can later displace these observations to a position, relative to the moving synoptic features in the wind field, which will correspond to the position of the observer, relative to these same synoptic features, at the time the observations were made. For example, an observation taken three hours before map time would be plotted in pencil at its reported position and, if the analyst found a cyclone in the vicinity moving westward at a speed of 15 knots, he would mark a point on the map 45 nautical miles to the west of the original position and replot the data in dark ink at that point. Similarly, observations taken after map time would be displaced to the east in this situation.

In figure 4-19 we see the data from two weather reconnaissance flights plotted in the conventional manner. The cardinal isogons (section 4442.) indicate the complexity of the wind pattern represented by the plotted data. In figure 4-20 the same data have been replotted, with each observation displaced to a more representative position relative to the main synoptic system in the area. In figure 4-21 we see a wind analysis drawn for the replotted data. The difficulty of mentally juggling the data to arrive at this analysis from the original plot illustrated in figure 4-19 is obvious.

When analyzing charts at 12 or 24 hour intervals, some forecasters use this method of displacing the data to make use of intermediate wind observations. The method is particularly useful when working with numerous inflight wind reports. However, great care must always be exercised to avoid moving the data incorrectly and thus doing more harm than good. Of course, the analyst must determine the displacement of the data himself, since a plotter has no means of determining the movement of the synoptic systems.

4440. Streamline Analysis.

While at the present time it appears that the best method of representing wind fields is in terms of streamlines and isotachs, there are two methods of achieving this analysis during practical work. In the first method, interpolations among the winds are carried out by eye, the accuracy attained depending upon the skill of the analyst in drawing the streamlines directly; this method we shall call the direct method. The other method makes use of an intermediate set of lines called the isogons. An isogon is defined as a line joining points in the plane which have the same wind direction. In this procedure the isogons are first drawn to the observations, the interpolation being carried out continuously as in scalar analysis. Then small lines are ruled on each isogon, corresponding to the wind direction which it represents. Thus a large number of wind arrows, in addition to those already plotted, appear on the map, and the interpolation is carried out with far greater accuracy than could be obtained by the most skillful practitioner using the direct method. The streamlines are then drawn both to the original observed wind directions and to the interpolated ones based on the isogons, the end

result being, as before, a set of streamlines everywhere tangential to the wind arrows. The analysis of the isotach or speed field is the same in both the direct and the isogon procedures.

The isogon method, though accurate, is rather tedious and takes a long time. For this reason it is not generally fitted for routine use in weather stations, where time to be devoted to analysis is always limited. Its chief function is to serve as a tool of research, in investigations leading to the development of new synoptic models. Streamline analysis conducted in the weather station will probably be by the direct method. As this throws a considerable burden upon the experience of the analyst, and since natural skill also counts heavily, beginners in streamline analysis will be well advised to practice first the isogon method. It gives an intimate acquaintance with methods of interpolation for wind direction. Only later should they undertake direct analysis in the weather station.

4441. The Direct Method. Streamlines are defined as lines which are everywhere tangential to the wind vectors. Thus to find the wind direction at any point along a streamline, one draws a short tangent to it at that point. The chief error made during the streamline analysis by the direct method is to depart from this condition of tangency. After many years of isobaric analysis, the forecaster instinctively acquires the habit of neglecting small departures of the wind from its gradient value. Since it is impossible to draw an isobaric

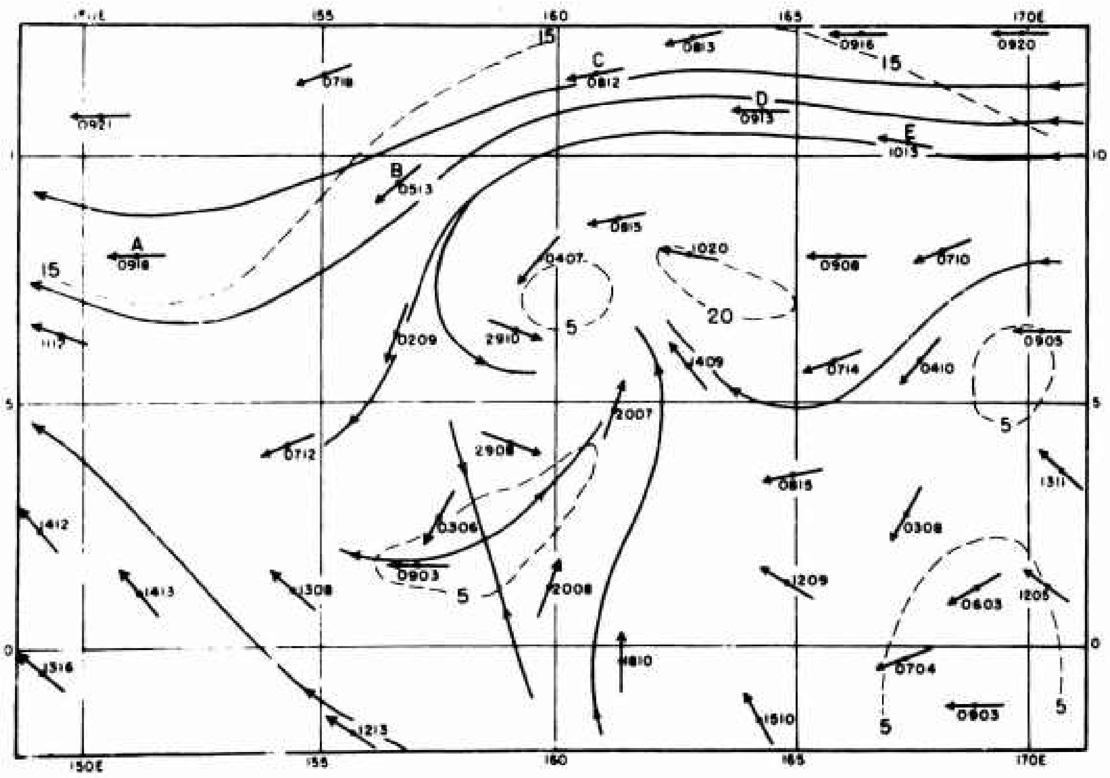


Fig. 4-22. A preliminary sketch of the streamlines and isotachs.

map on which the gradient wind relationship holds for every part of the surface analyzed, he learns to allow the isobars to cross the wind arrows at some small

angle. The analyst must break himself of this habit if he is to use the direct method of streamline analysis with any skill. In drawing a single streamline, he must, in his mind's eye, interpolate a host of imaginary wind vectors, between the observations of his network. Then he must draw lines which are tangential both to the observed winds and to these imaginary interpolated wind arrows. Obviously this is a difficult process to perform. The beginner should first examine the part of the map where the observations are densest and try to pick out one streamline that is almost straight or only slightly curved. In figure 4-22, for example, he could begin by sketching lightly in pencil a streamline that passes near the stations A, B, C, D, and E. Next he should observe whether the winds adjacent to this initial line are spreading apart, coming together, or are parallel to each other, and sketch his lines accordingly. Sketching of the streamlines should then continue until the pattern is completed (Fig. 4-23). The signal that the interpolation is complete and

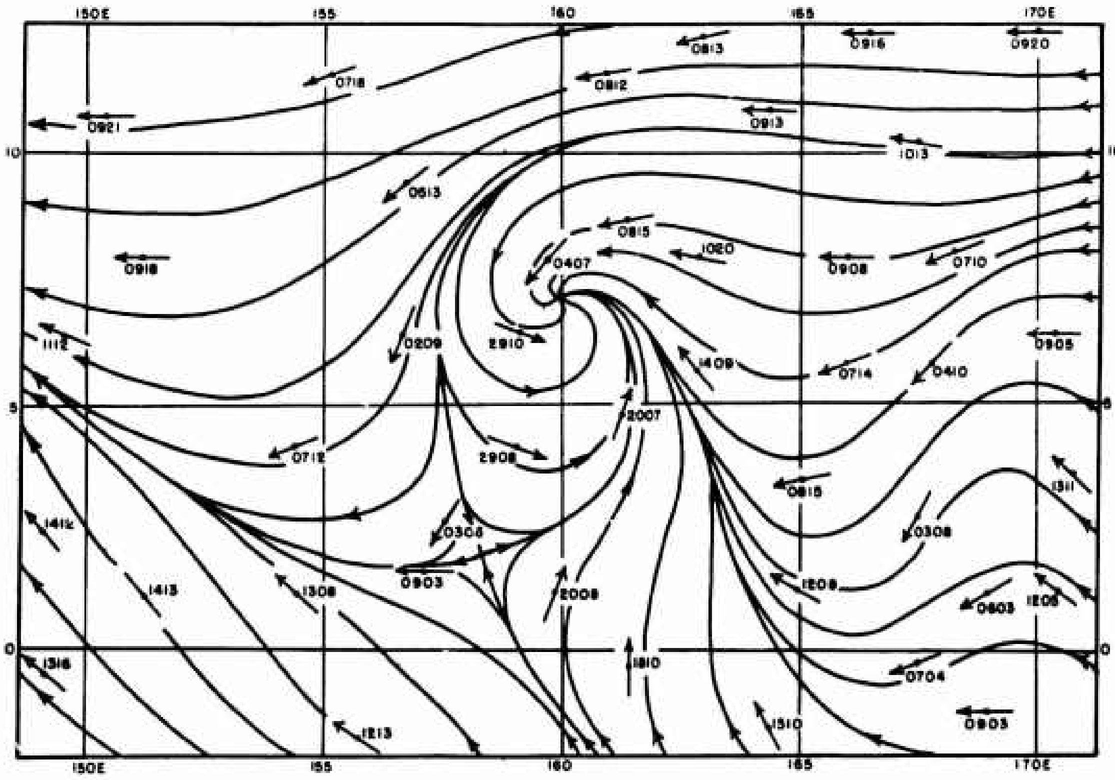


Fig. 4-23. The completed streamline analysis.

correct comes when the analyst recognizes that every wind arrow plotted is strictly tangential to the streamlines, that no streamline turns too abruptly, and that there is a general smoothness and elegance to the pattern, difficult to define but easy to recognize.

The typical streamline patterns and their relation to the speed patterns (discussed in section 4350) must be kept in mind at all times. Sketching a few rough isotachs as an aid in visualizing the speed field is helpful during this phase of the analysis. Of course, continuity from the previous analysis and from a level below the one being analyzed is one of the analysts

primary aids. Also, the use of certain auxiliary charts is another aid to wind analysis, as discussed in section 4600.

Experience shows that very great complexity of wind pattern, though physically possible, very rarely occurs in the atmosphere and then only near the surface over rough ground. In any graphical field analysis the number of lines of representation which can be drawn is, in theory, infinite. However, in scalar analysis it is customary only to draw lines for multiples of some standard value of the scalar magnitude. Thus, in pressure analysis, it is customary to draw isobars in 2 milibar or 3 milibar intervals. This automatically determines the spacing of the lines in the pattern of the analysis. In streamline analysis, on the contrary, the streamlines do not represent any particular magnitude; their sole property is that the wind vectors are tangential to them. Therefore, the number of streamlines used in a representation is quite arbitrary and is a matter of analytic convenience. Sufficient streamlines should be drawn to give an adequate representation and to enable the wind direction to be read easily at any point.

In passing, it should be mentioned that the commonest difficulty encountered by the beginner is occasioned by the tendency to distort the streamlines to make them pass through the stations where data are plotted. This tendency often leads to departure from the condition of tangency.

<u>4442. The Isogon Method.</u> In using isogons, advantage is taken of the experience which most forecasters have in interpolating among a set of plotted observations in the form of numbers. Tropical wind fields rarely show anything that approximates to a discontinuity of wind, such as a front, therefore, if we have a set of observations of wind direction, say for the value 100 degrees, separated by a relatively narrow space from another set of observations where the wind directions are of the value of 120 degrees, we are justified on the principle of continuity in supposing that in the intervening space, the winds have values intermediate between 100 and 120 degrees. We can draw a line through the first set of observations and label it 100 degrees. A similar line labeled 120 degrees may be drawn through the second set of observations; we are then justified in interpolating, between the 100 degree isogon and the 120 degree isogon, an isopleth which will be labeled 110 degrees. We use the same principle in isobaric analysis.

Isogon analysis, however, is not as simple as ordinary scalar analysis, such as the temperature or pressure fields. Corresponding to the singular points of the streamline field, the isogons themselves will end in points where the wind direction is indeterminate. In addition, of course, they can be closed curves (Fig. 4-24).

The idealized isogon patterns associated with certain typical streamline patterns are illustrated in figure 4-25. Notice that the closed isogons associated with the wave increase in number as the wave increases in amplitude. The isogons become tangential to each other at the cusp point and appear to intersect in the vortex and in the neutral point. Upon closer examination it will be seen that each isogon which intersects another actually represents opposite directions on either side of the intersection. However, it is convenient to draw the isogons for opposite directions as continuous lines when

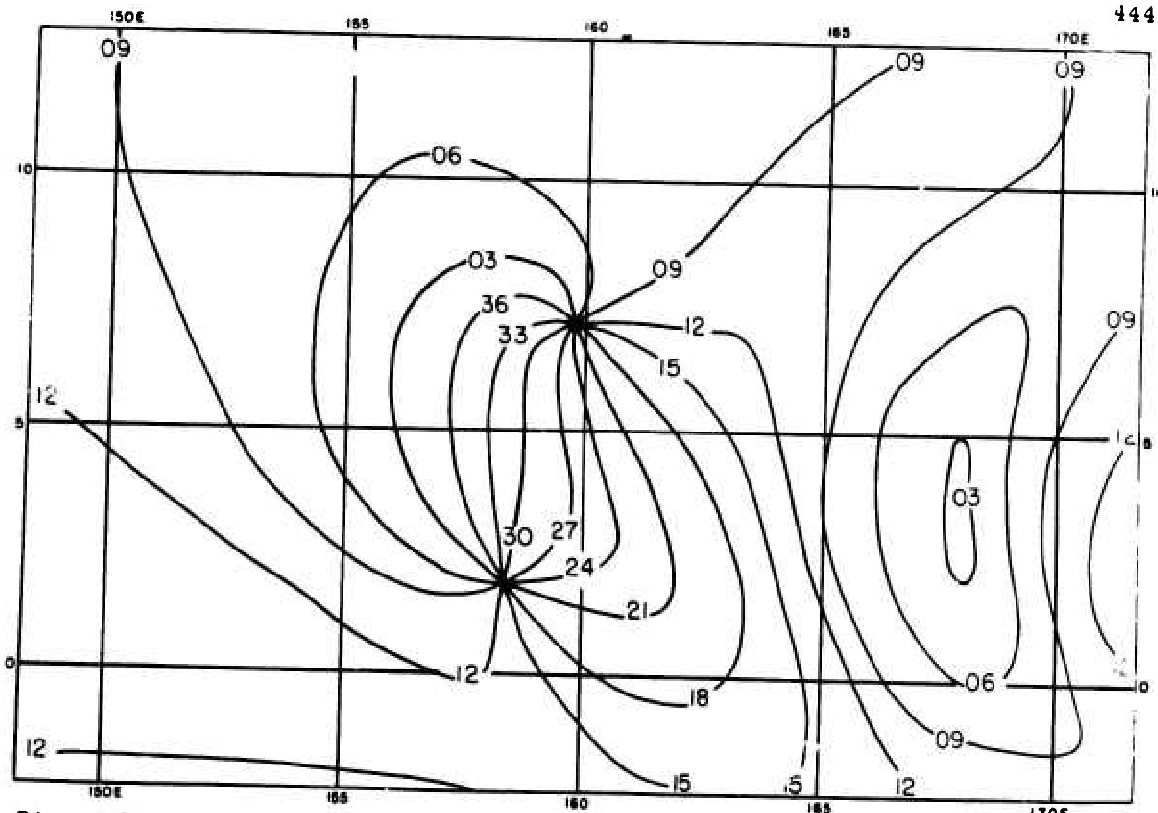


Fig. 4-24. A complete isogon analysis illustrating singular points and a closed curve in the isogons.

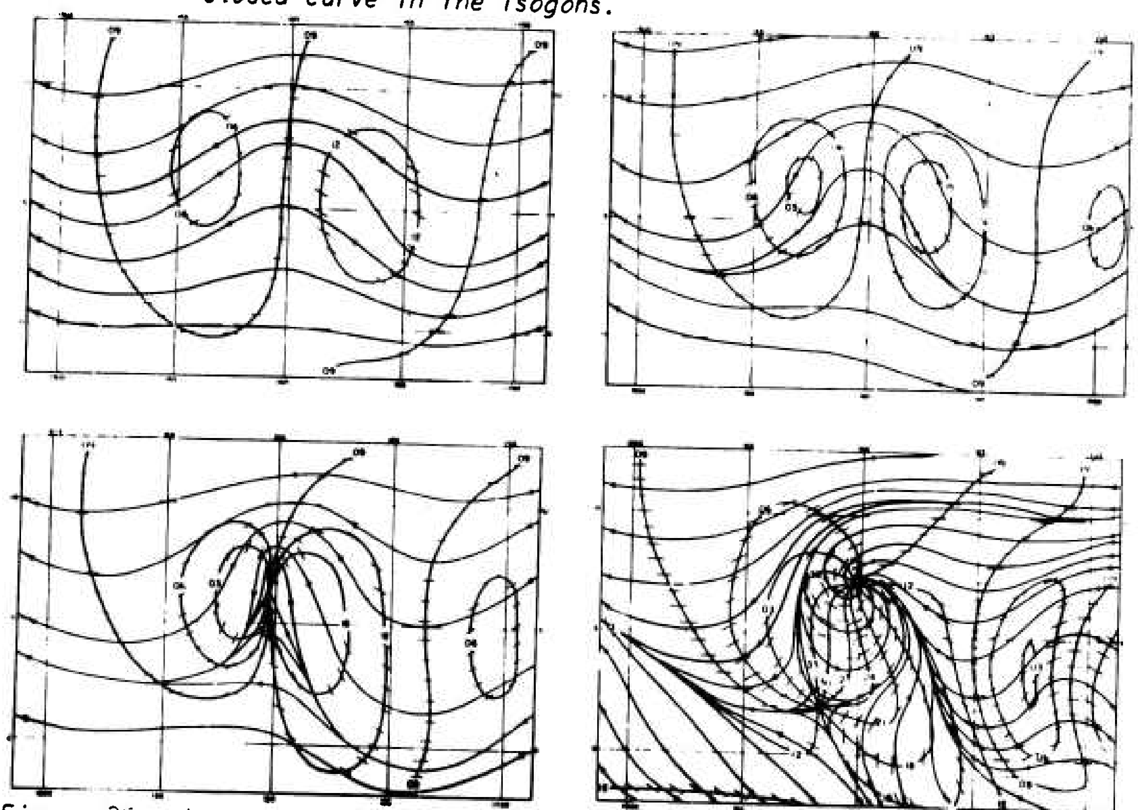


Fig. 4-25. Isogon patterns associated with common streamline patterns.

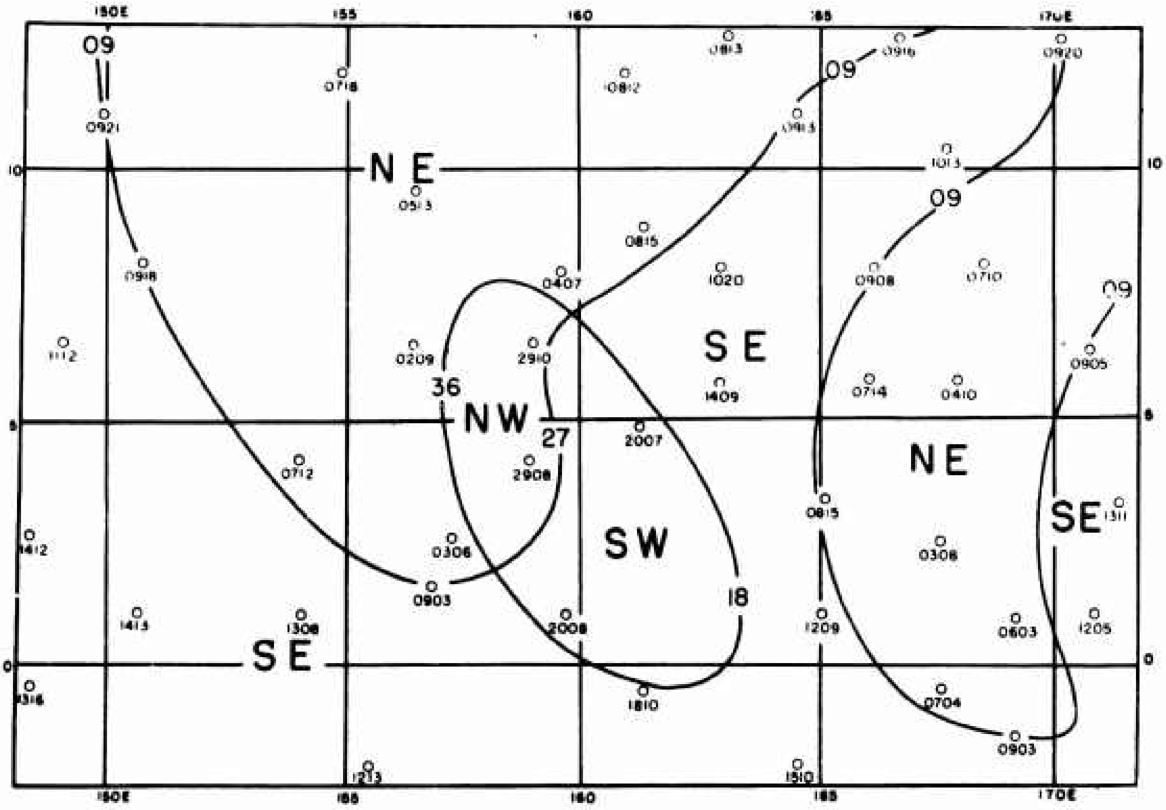


Fig. 4-26. A preliminary sketch of the cardinal isogons.

they come together in a singular point. The analysis in the vicinity of singular points can be accomplished most easily by first sketching the isogons for the cardinal directions to determine the basic outline of the isogon patterns (Fig. 4-26).

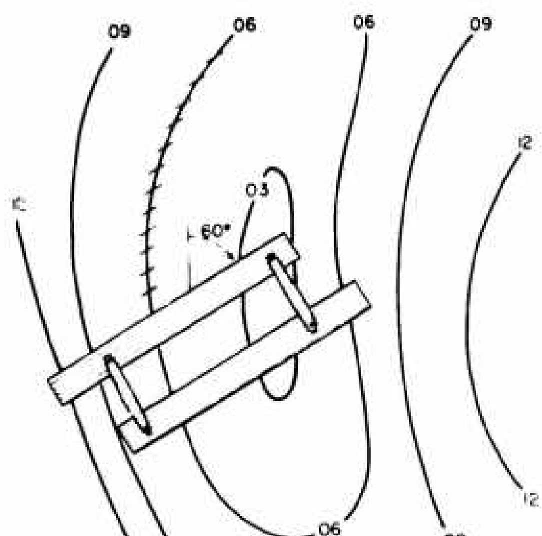


Fig. 4-27. Drawing the line elements with parallel rulers.

It remains to discuss the mechanics of passing from a completed isogon analysis to the final streamline analysis. Each isogon should be labeled with its value in tens of degrees from 1 to 36. It is not necessary in all parts of the map to draw every isogon from 1 to 36. For most purposes isopleth intervals of 30 degrees will be sufficient, starting with 3 and continuing to 6, 9, 12, etc. However, in broad regions where the wind as indicated by the observations shows little change in direction, it is sometimes an advantage to draw some additional isogons to assist in the final analysis.

The next step in the analysis consists of taking parallel rulers and a protractor, orienting the ruler with respect to the grid on Mercator's projection and ruling, along each isogon, short line elements

(not more than ¼ inch in length), corresponding to the indicated value of the isogon. The process is illustrated in figure 4-27. Along isogon 6 the rulers, previously oriented to the direction 60 degrees, are moved in stepwise fashion and the line elements are ruled at convenient intervals. Intervals between rulings can be easily judged after a little experience; it should be remembered that the aim is to cover the map, fairly uniformly and without excessive overlapping, with small direction lines (arrows without heads).

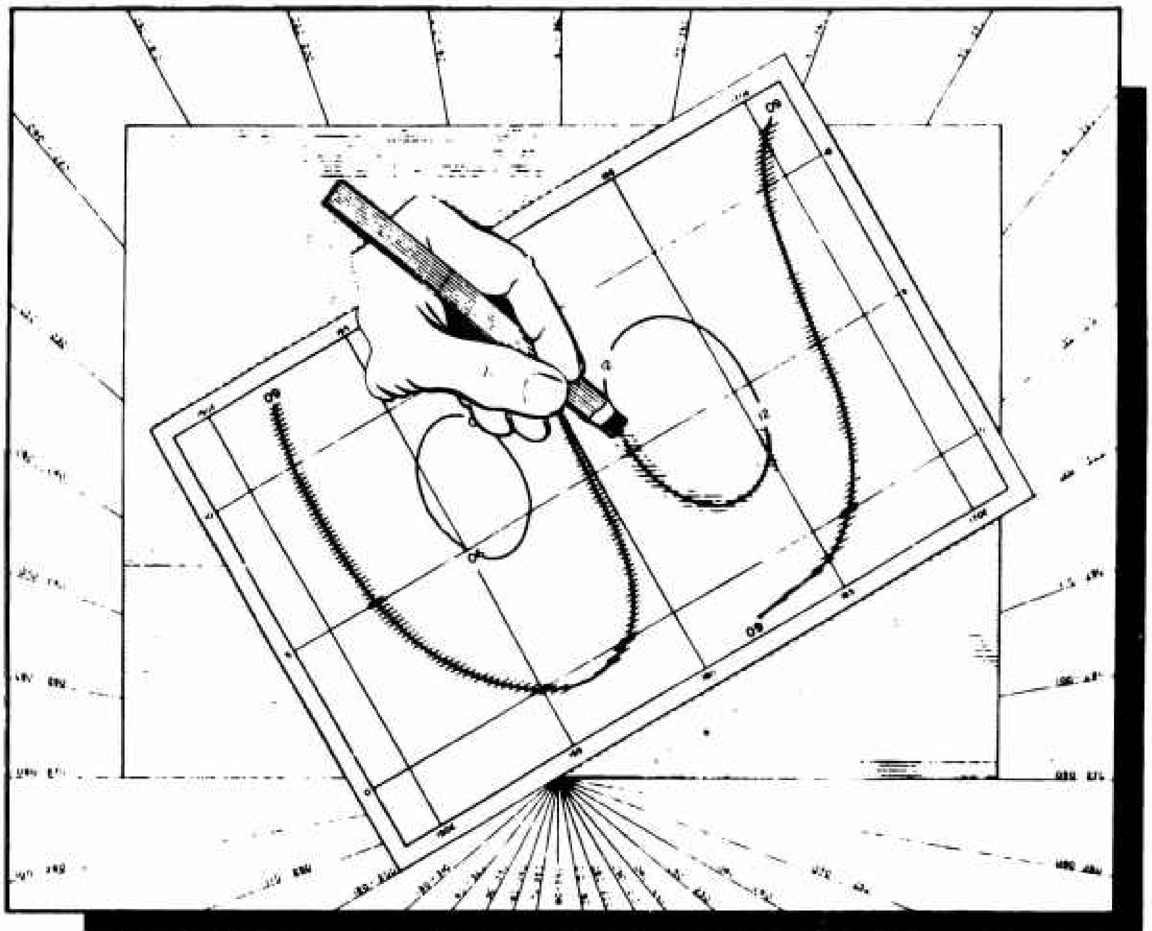


Fig. 4-28. Drawing the line elements with an isogon board.

Another method of ruling the isogon line elements is to place the chart over a corrugated glass panel oriented in such a way that rubbing over a given isogon with a crayon will produce line segments on the map which are oriented in the direction represented by the isogon being traced. The map is then reoriented for another isogon and the process repeated until line elements for all of the isogons have been ruled on the map. The corrugated glass panel may be mounted in a frame and the directions represented by the isogons marked on the frame to help orient the map for ruling each isogon (Fig. 4-28).

When the map is covered in this fashion with line elements, it becomes a simple matter to draw the streamlines (Fig. 4-29). Again, the analyst must rigidly adhere to the principle of drawing the streamline tangential

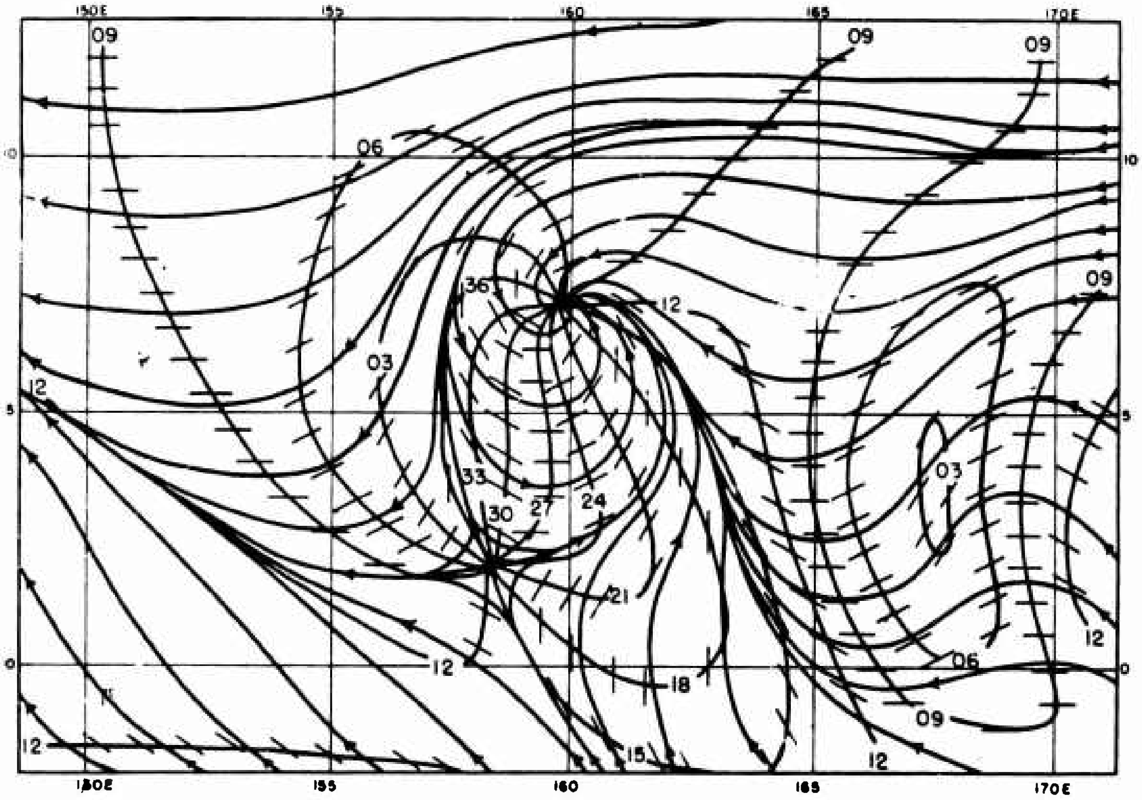


Fig. 4-29. Streamlines drawn with the aid of the isogon line elements.

to the line elements. Great assistance in keeping to this requirement is given by certain auxiliary lines, very easily sketched after the rulings have been completed but before the final streamlines are drawn. These auxiliary lines are of two kinds -- the inflection lines, which do not appear in the final analysis, and straight line asymptotes, which do.

Consider the streamline shown on Figure 4-30. It shows two kinds of curvature: on the left it has positive curvature (cyclonic in the Northern Hemisphere); on the right, negative curvature (anticyclonic in the Northern Hemisphere). Necessarily, in passing downwind along the streamline from one side to the other, we must pass through a point where the curvature is zero. This point is the inflection point. If we have several neighboring streamlines, each with a point of inflection, we could draw a line joining these points. Such a line would be called the inflection line. The inverse process which aids the analysis is to obtain the inflection line before drawing the streamlines. Obviously in sketching a streamline, if we know when we are crossing the inflection line, the process is greatly simplified. The analyst knows that the curvature will be of one sign on one side of the line and of the opposite sign on the other. Without entering into the theoretical reasons for the statement, we may state that the inflection line will pass through points where the line element is tangent to its own isogon. A simple example is illustrated in figure 4-31. Notice that every closed isogon has at least two points at which the ruled line element is tangent to its own isogon. The appearance of a closed isogon, therefore, is a sign to the analyst that a line

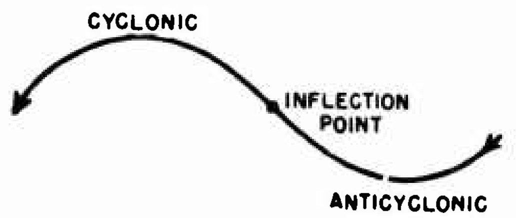


Fig. 4-30. An inflection point on a streamline.

of inflection exists in the vicinity and it is often a great advantage to start by sketching the inflection line in such a region.

The second type of line which is easily recognized in the isogon field, immediately after the line elements have been ruled, is the straight line asymptotes, usually found in the vicinity of a singular point. For any segment of a streamline to approximate a straight line, thus having the same direction at successive points, it must lie along a straight isogon. When this streamline is also an asymptote the streamlines on either side must cut across the isogons in opposite directions. Consider the four isogons 8, 9, 10, and 11 in figure 4-32. The winds are obviously easterly in general direction, so that small arrow heads may be imagined attached to the left hand end of each element.

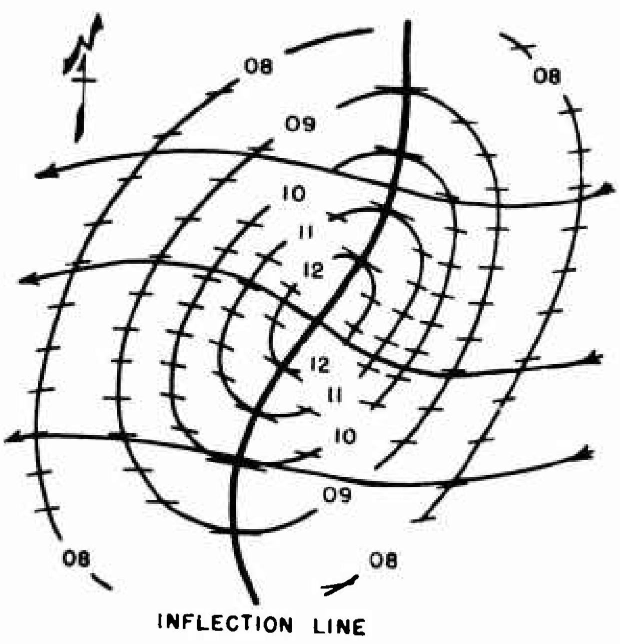


Fig. 4-31. An inflection line connecting the inflection points on neighboring streamlines.

Looking downstream, the line elements cross the isogons 8 and 9 from right to left, whereas on 10 and 11 they cross from left to right. If the winds are varying continuously, then, an intermediate isogon lies between 9 and 10, along which the isogon and line elements have the same direction. This line may be sketched in lightly by trial and error. It will represent a definite streamline and hence will appear in the final analysis. On the left of this line the streamlines will run across the isogons from the left; similarly, on the right they will converge toward it from the right. It is therefore an asymptote of convergence and the method outlined will enable it to be located with great accuracy. Before drawing the streamlines and after having put in the inflection lines, the analyst should always look over the field of ruled isogons in order to find these easily detected asymptotes. However, he must not expect to find them on every map. As already stated, they are most apt to occur in those parts of the analysis where singular points have already been found.

Even when a complete isogon analysis is not practical, forecasters will find it helpful to use the isogons over limited areas where the streamline patterns are complex. The continuity in the isogons is sometimes easier to follow than that in the streamlines themselves.

4450. Isotach Analysis.

The direct method and the isogon method of streamline analysis differ essentially only in the manner in which the interpolation for wind direction is

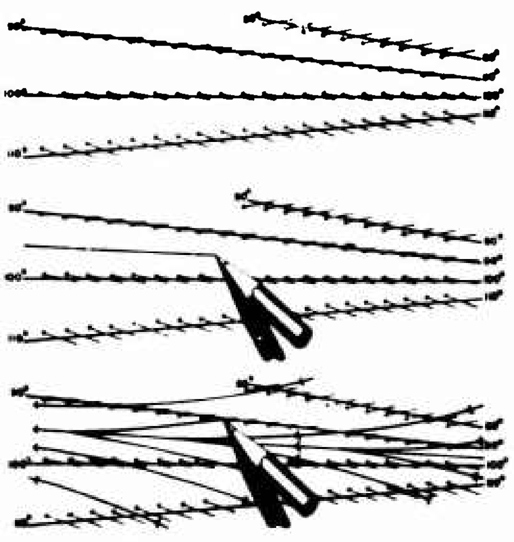


Fig. 4-32. Locating a straight line asymptote.

carried out. The remainder of the analysis, that is, the delineation of the speed field, is the same in both the direct and isogon methods. It is understood, of course, that the analyst has not neglected wind speeds during the drawing of the streamlines. The final speed analysis, however, which is now to be undertaken, consists in the drawing of a completely new set of lines. These differ from the streamlines in that they are numbered curves not terminating in singularities, that is, they are entirely similar to the curves drawn in a scalar analysis such as that of the pressure field. The analyst who is already familiar with scalar work should have very little difficulty with interpolation and with drawing the lines. He will expect to find col points and areas of maximum and minimum values of the speed just as he expects to find highs, lows, and cols on a pressure analysis. His knowledge of the relationships between the streamline patterns and the isotach patterns (see section 4350) must be applied during this phase of the analysis, and, of course, continuity from the isotach patterns on the preceeding map is one of his primary tools. It is customary to draw isotachs at 5 knot intervals in the tropics. If isotach analysis is carried out in high latitudes, say in the neighborhood of the jet stream, these intervals will probably be too close; 10 knot or 20 knot intervals should then be used. The isotachs should either be drawn directly over the streamlines or can be first sketched on a transparent sheet, superimposed over the streamline analysis. Then the final transfer from the transparent sheet to the base map can be made on the light table. The first step in the isotach analysis is to examine the position of all singular points in the streamline field. As previously pointed out, these are places where the wind reaches an absolute minimum, i.e., zero. Consequently, one expects to find a closed 5 knot isotach surrounding a singular point or, in the case when two singular points are close together, enclosing both of them. Some minima of the speed field, then, are easily found; they are the minima at the singular points. But minima in speed may occur in other parts of the map, and this fact must not be forgotten as the isotachs are being drawn.

The second step in the isotach analysis is to locate the elongated speed maxima in the major currents, such as the trade winds, and draw the isotachs outlining them. Then the smaller features should be outlined and the remaining isotachs drawn to complete the field. Since errors and fluctuations in wind speed occur with greater frequency than in wind direction, a certain amount of smoothing is permissible. The aim should be to present a simple speed regime whenever possible. Figure 4-33 illustrates a completed streamline and isotac analysis.

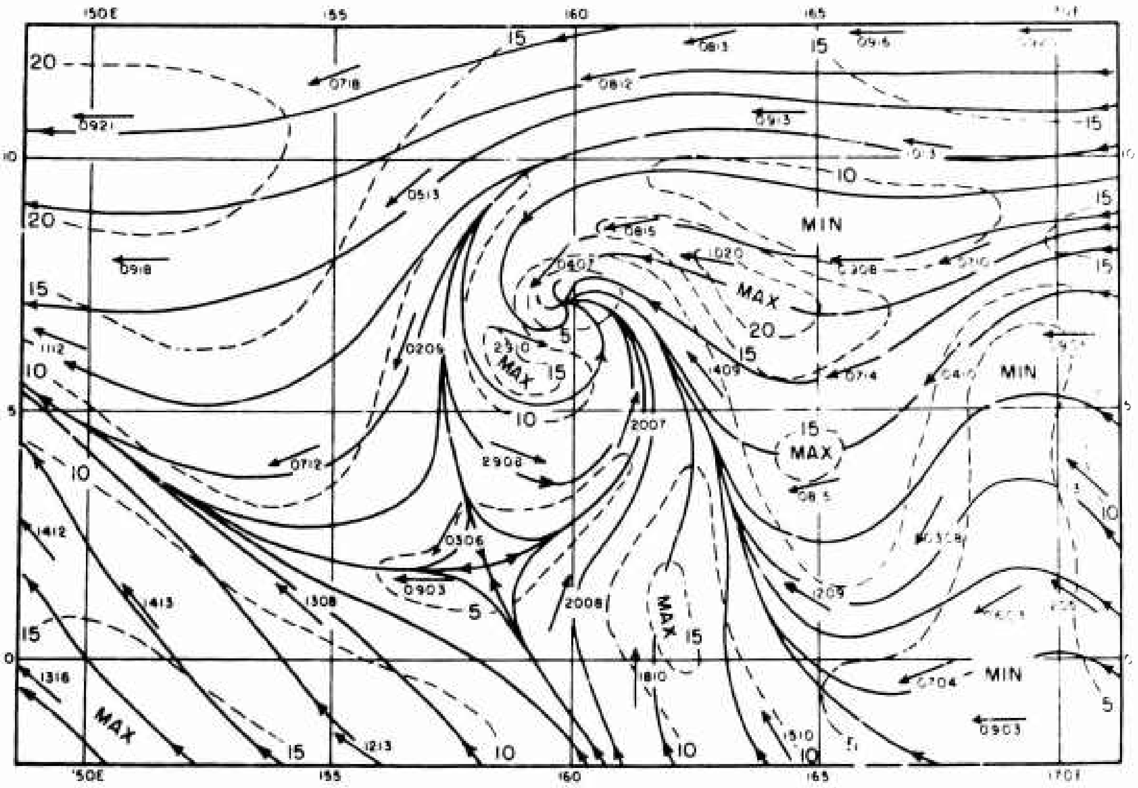


Fig. 4-33. A complete streamline-isotach analysis.

4460. Completing the Wind Chart.

When both the streamlines and the isotachs have been completely sketched, preferably on transparent overlays, the analysis is essentially complete. However, the graphic representation of the analysis requires additional steps, such as tracing the streamlines and isotachs in distinctive colors, drawing sufficient arrow heads on the streamlines to indicate clearly the direction of flow, labeling the vortices and centers of maximum and minimum speed, and any other artistic refinements dictated by the particular uses to be made of the chart.

4500. THREE-DIMENSIONAL STREAMLINE MODELS.

The forecaster who has studied the preceding sections has become familiar with the various wind flow patterns within a horizontal plane or surface. He cannot hope to make a true analysis of the synoptic wind field, however, without a thorough understanding of the three-dimensional structure of the typical wind patterns, the asymptotes, waves and singular points.

4510. Asymptotes.

Asymptotes which appear in the streamlines have three-dimensional structures which may be thought of as vertical or sloping surfaces or narrow zones, in some ways analogous to the fronts of high latitudes, lying between converging or diverging currents having vertical depth (Fig. 4-34). We are primarily interested

4510.

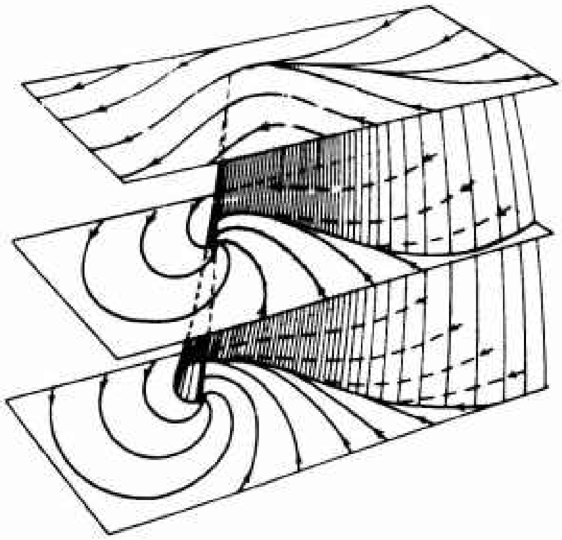


Fig. 4-34. Three dimensional structure of an asymptote in the streamlines.

in the negative asymptotes lying between converging currents since, in the lower levels, they are most frequently associated with bad weather. (See section 6000)

Significant negative asymptotes are most frequently found in the convergent flow around well developed cyclonic indrafts and in the broad zone of convergence between the tradewind currents of the two hemispheres.

The slope of asymptotes varies from vertical to quasi-horizontal. However, those asymptotes whose slopes approach the horizontal appear only in the vertical component of the wind and are not seen in the horizontal streamlines. The slope may also vary from point to point along a given asymptote and, in a particular segment, may vary with height, even to the extent of being reversed from one level to the next. For example, an east-west asymptote may slope toward the north in the lower levels, become vertical at some intermediate level, such as 10,000 feet, and slope back toward the south above that level. Very little work has been done toward evaluating the slope of asymptotes. However, Watts (1949) in writing about the primary asymptotes of the Malayan-East Indies area states:

> The equatorial equivalents of the Intertropical Front are the Northern Equatorial Convergence Line and the South- Equatorial Convergence line. The Northern Line is th of latitude 10° North from May to October to consti- te the Intertropical Front of the Northern Hemisphere. e Southern Line passes south of latitude 10° South at times during February and March to become the Intertropical Front of the Southern Hemisphere, and during April and May the two lines frequently coincide in the equatorial area east of longitude 106° East. When and where the lines are not coincident, they are normally separated by a Westerly Equatorial or Southwesterly Monsoon current.
>
> The mean slope, from ground to 10,000 feet, of the convergence surface through the Northern Equatorial Line is 1 in 70, and is always steep.
>
> The mean slope, from ground to 10,000 feet, of the convergence surface associated with the Southern Equatorial Convergence Line is 1 in 210. Individual cases constitute a great range on either side of the vertical, but slope is generally upwards to the southeast with Equatorial Westerlies overlying the Southwest Pacific southeasterlies.

> The slope of either convergence surface, in the layer ground to 10,000 feet, is usually increased in movements of the surface line analogous to cold front movements and reduced by those analogous to warm front movements; but these changes are not discernible in the layer ground to 5,000 feet.
>
> The slope of the convergence surfaces through both the Equatorial Convergence Lines changes with some regularity.
>
> The period of these changes is about one week or slightly more, and the changes are believed to be dependent on the positions of the migratory anticyclones of the Southern Hemisphere.
>
> Owing to the frequency and magnitude of changes of slope, it is unlikely that practical use could be made of any conceivable adaptation for low latitudes of Margules Formula. In support of this it may be noted that, although slope is no doubt dependent on the relative densities of the two masses and on wind-components normal to the separation-line, the convergence lines at various altitudes are not always coplaner.
>
> Thus, an equation for slope could not be of instantaneous application to the entire separating boundary.
>
> Both cumuliform and altostratus clouds are representative of the Equatorial Convergence Lines; the altostratus is a product of the spreading of cumulus and cumulonimbus tops, and does not result from general ascent of the sloping surface in the fashion of a temperate-zone warm front.

In this paper Watts also states, with reference to the convergence surface associated with the Southern Convergence Line:

> It is found that there is a tendency for the slope to be adjusted to the variation with altitude in the resultant wind normal to the convergence line. That is to say, the slope is altered gradually, following the sense of the difference at each level between the component normal to the convergence line in the southeasterlies, and in the westerlies. Therefore if at upper levels the wind-component normal to the convergence line is greater in the southeasterlies than in the westerlies, the slope tends to the vertical or to overturn to the northwest. But the exact relation is obscure, because the magnitudes of velocity are difficult to determine, and the differences of the normal components are frequently as small as their probable errors.

While it is true that the ideas quoted above have been applied to only one small area, and are not time proven, they may suggest a practical approach to the problems of analysis and forecasting associated with the major asymptotes of other areas in the tropics.

4520. Waves.

Waves which appear in the streamlines have a three-dimensional structure which should be examined by the analyst. For instance, a wave appearing in the streamlines of the surface or 2,000 foot winds may be damped with height, extending vertically only a few thousand feet before disappearing, or its amplitude may increase with height (Fig. 4-35). Those which increase in amplitude with height are usually associated with upper level cyclones or upper

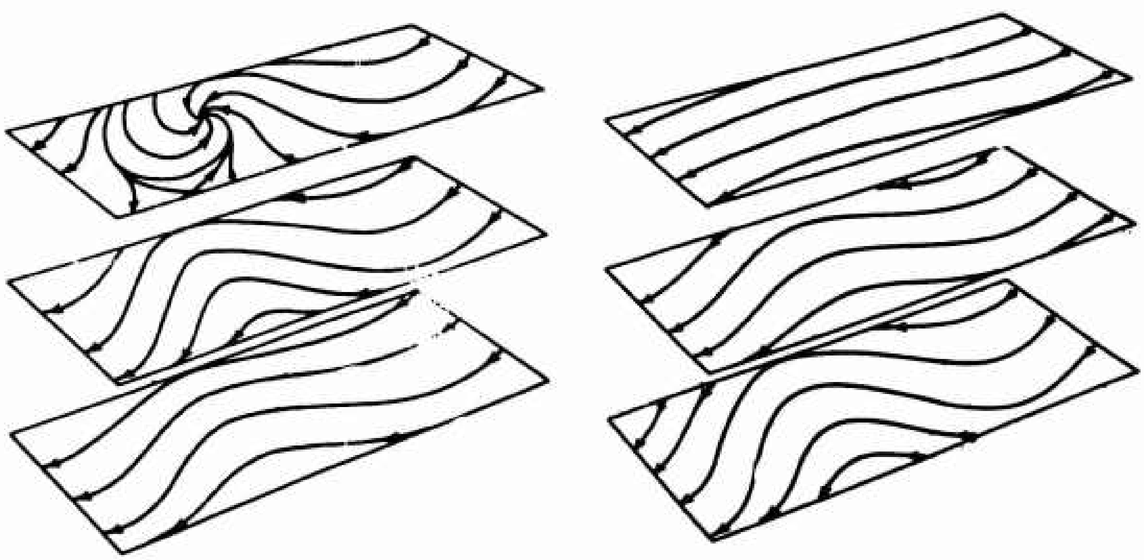


Fig. 4-35. Three dimensional structure of waves in the streamlines. They may increase in amplitude with height, left, or decrease in amplitude, right.

level troughs in the westerlies. Distinguishing between the two types of waves is essential since their behavior may be entirely different.

Those waves which are damped with height generally move at a uniform speed in the direction of the current in which they are embedded. The easterly waves of the Caribbean, Western Pacific and Eastern Atlantic are examples of this type of wave.

Waves, which are associated with an upper-level vortex or trough, generally move with the upper-level feature, which may be in a direction opposite to that of the low-level current. The situation is further complicated when a weak wave in the easterlies moves under an upper-level disturbance. In this case the wave will usually increase in amplitude as it approaches the position of the upper level vortex, or trough. Thereafter, the wave may remain with the upper level feature, or it may continue its westward movement independently; in which case a new wave may appear beneath the upper level disturbance.

The axis of a wave may be vertical or may slope either forward (in the direction of movement) or backward, with height. A thorough examination of the wind "time-sections" (see section 4610), for stations over which the

wave has moved will help determine the slope of its axis. This is important because the slope of the axis is believed to be associated with the weather accompanying the wave.

4530. Singular Points.

Singular points appearing in the horizontal streamlines actually represent the intersection of a vertical line singularity with the plane of the streamline analysis. That is to say, the vertical axis of a three-dimensional vortex or neutral point is a line which joins the center or axis of the singular point as it appears in the streamlines at successive levels.

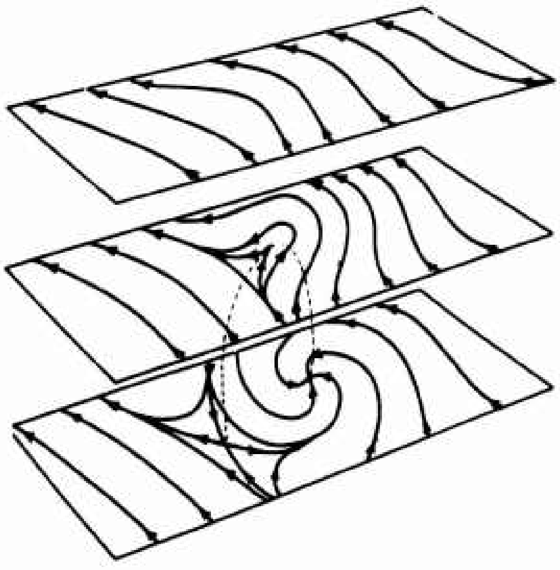


Fig. 4-36. Three dimensional structure of a vortex-neutral-point pair at low levels.

In discussing the three-dimensional model the vortex neutral point pair will be treated as a single unit. In the transition from a wave to a vortex in the horizontal streamline patterns we saw first the cusp point and then the vortex-neutral-point pair appear. Examining this transition in the vertical, we see the cusp point appear near the surface then move upward as the vortex-neutral-point pair emerges. The cusp point itself has no significant vertical depth and may be seen at one level only, at a given time. However, the vertical axes of the vortex and the neutral point always remain joined in a cusp point at some upper level, and above that level the wave appears in the streamlines for at least a short distance vertically (Fig. 4-36).

A three-dimensional model of a vortex-neutral-point pair which exists entirely at upper levels has the same form at both its upper and lower extremities. That is to say, the vertical axes of the vortex and the neutral point are joined in a cusp point at both the upper and lower limits of the model. The point at which the vertical axes are farthest separated represents the level at which the circulation around the vortex has its largest radius (Fig. 4-37).

Of course, either the upper or lower portions of the model may be destroyed by intersection with a strong shear layer, and the lower portion of an upper level model may be destroyed when it extends downward to intersect the surface of the earth (Fig. 4-38).

The cyclonic indrafts, which frequently form in the tradewind currents and sometimes develop into intense tropical cyclones, are typical of the low level type of vortex-neutral-point model. They generally move westward at an average speed of 10 to 15 knots while still embedded in the trade wind current.

The so called "Kona Storms," of the Hawaiian Islands area are associated with the upper level vortex-neutral-point model. Little is known about the

movement of these disturbances. However, they often remain almost stationary for a week or more.

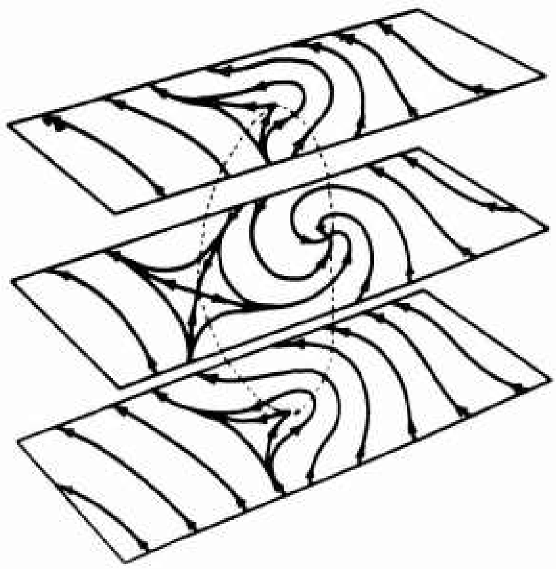


Fig. 4-37. Three-dimensional structure of a vortex-neutral-point pair at upper levels.

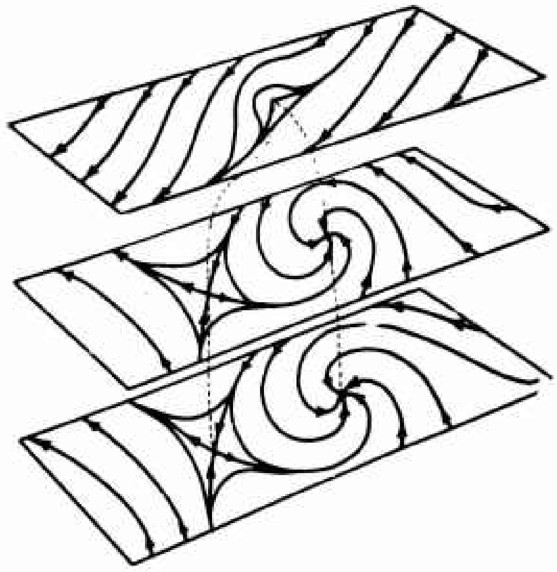


Fig. 4-38. Three-dimensional structure of a vortex-neutral-point pair which intersect a shear layer, upper plane, and the earth, lower plane.

The axis of either the lower level or the upper level type of cyclonic vortex may slope in any direction, but the tilt from the vertical is usually slight. The axes of the large subtropical anticyclones, however, decidedly differ from the vertical, usually sloping upward to the west and toward the equator. It is not unusual for the axes of the anticyclones to be displaced equatorward as much as 15 degrees of latitude in the lower 20,000 feet.

4600. PRACTICAL AIDS TO ANALYSIS.

The meteorologist attempting routine analysis in the tropics for the first time is likely to be dismayed or even disheartened by one feature in which the observing networks differ from those of higher latitudes, that is, the great distances between observing stations. Even the stations which report only surface conditions are, generally speaking, much farther apart than they are in high latitudes; the density of ship reports, likewise, is lower over the tropics than over the temperate zones of the ocean. But the most serious lack of information becomes evident when any type of upper air analysis is attempted. Rawinsondes, on the average in the tropics, are one thousand miles apart. In certain regions, many thousands of square miles in extent, they are entirely lacking, the only upper-air soundings being in the form of pilot balloon observations. In these regions the forecaster must depend upon in-flight weather reports from transient aircraft for a large part of his upper air data.

Under the circumstances, the forecaster has to extract from the few upper air observations coming into his station the maximum amount of information.

In some areas he has to conduct what amounts to single station analysis and forecasting. Since wind analysis, for the reasons already outlined, takes precedence at tropical stations over contour or pressure analysis, he requires facilities for studying as efficiently as possible the time changes in the upper winds at each of the observing stations and along each of the routes within the area of his greatest interest. Certain auxiliary charts assist the study and forecasting of upper winds very greatly; in certain cases, carefully analyzed auxiliary charts can actually eliminate the need for many of the synoptic charts normally analyzed each day.

4610. The Time-Section.

The time-section is simply a form for recording the upper wind observations and surface synoptic observations as they come into the weather station. An example is shown in figure 4-39. The form is arranged in such a way as to display, at a glance, the upper winds and three-hourly surface observations, from a given station, for a period of three days. The vertical rows of dots on the form represent the axes of the upper wind soundings. At each side of the form the various levels from the surface to 55,000 feet are indicated, the surface winds being recorded in the lowest horizontal row. A separate time-section is maintained for each station in the area of interest. As each wind report for a station under analysis is received, the directions (isogon values) are plotted on the left hand side of the vertical axis, the speeds on the right.

The data from surface synoptic observations are entered in the spaces provided on the lower part of the form. Plotting the data in vertical columns provides a convenient means of observing the changes, with time, in each individual element. The method of plotting may be adapted to local needs and, of course, the form may be varied to accommodate the elements reported in the various WMO Regions. Blank spaces are provided for recording other pertinent data, such as the 24-hour pressure change, which the forecaster may wish to examine. When scheduled observations are not received the appropriate spaces should be left blank.

The time-section is used primarily as a means of examining the continuity in the plotted elements, during the time intervals between synoptic charts and in the space interval between the levels of analysis. When dealing with the fast-moving, well-defined, synoptic systems of high latitudes, it has become the custom to plot and analyze synoptic charts at very short time intervals. By comparison, synoptic systems in the tropics are generally poorly defined, change slowly with time and move slowly. Therefore, there is little need to analyze synoptic charts at frequent intervals during the day, provided the data are compiled on a form from which they can be assimilated easily by the forecaster. When the forecaster has learned properly to interpret the changes occurring in the data on his time-section, he should be able to work efficiently with only one set of synoptic maps daily. Of course there may be times, during complex synoptic situations, when intermediate charts will be required.

Merely having the data presented on the time-section form is a great aid to the forecaster. There are also several forms of wind analysis which may be performed on the time-section. These analytic procedures enable the forecaster to identify systematic patterns in the changing winds at

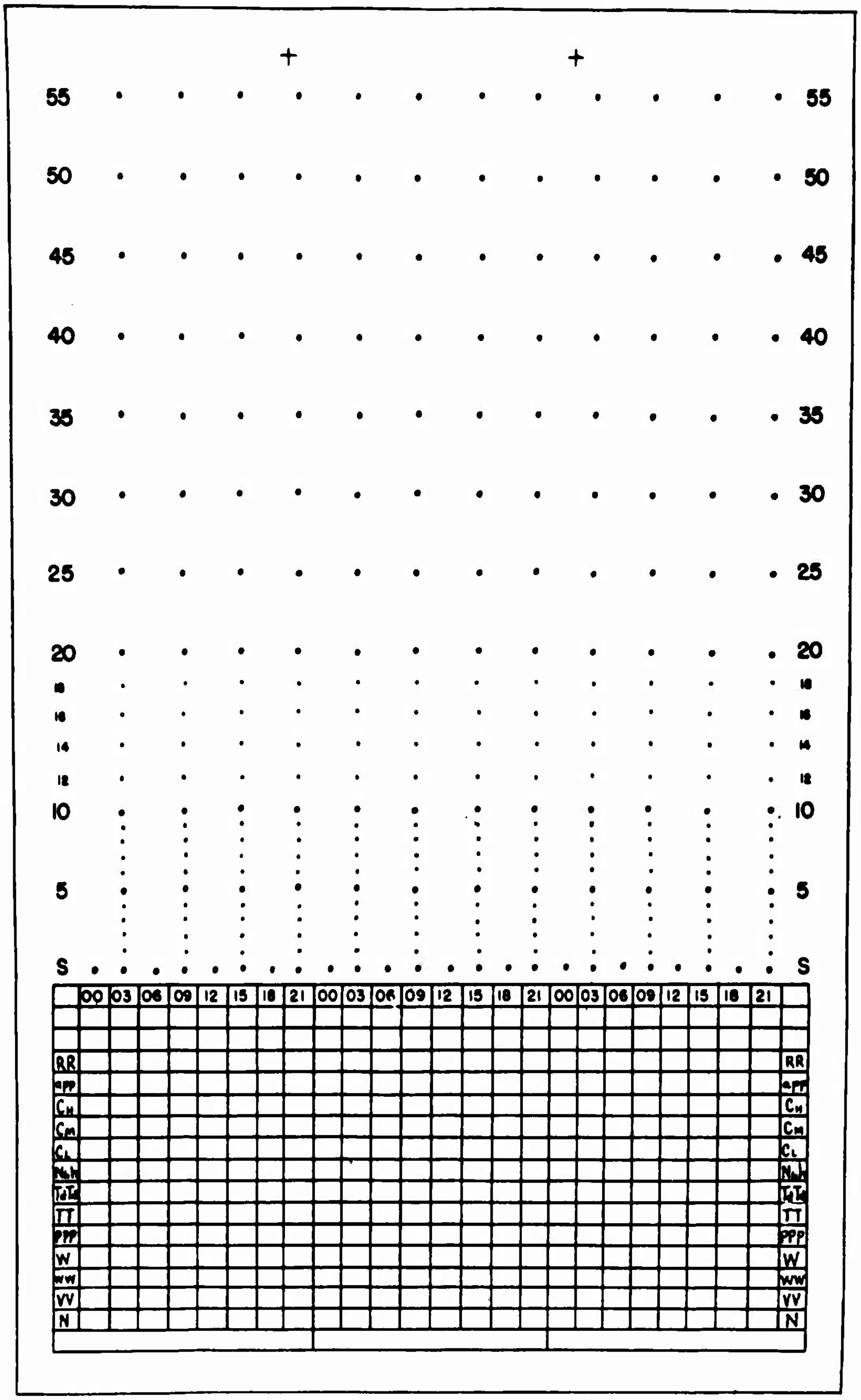


Fig. 4-39. Example of a time-section form.

each station and provide a means of recording the patterns.

The type of analysis to be performed, and even the necessity of doing an analysis at all, will vary between individual stations and with seasonal or synoptic changes at any given station. The selection of stations for which the time-section should be maintained is a problem that varies for each forecast center. Naturally time-sections should be maintained for the home station and all upper wind stations within the area for which forecasts are issued. It should be remembered, however, that a correct analysis in a given area sometimes depends upon the study of time changes at stations quite remote from the immediate forecast area. It must be emphasized that the time-sections can be used only in conjunction with the synoptic maps and, therefore, cannot replace them entirely.

4611. Analyzing the Wind Directions. Isogons may be drawn on the time-section in the same manner as they are drawn on the horizontal wind charts. The dots of the time-section replace the station circles on the map. The isogon patterns on the time-sections are also similar to those on the synoptic wind maps, i.e., there are closed curves and singular points in the field. Identifying these features on the time-section and observing their association with the changing synoptic wind patterns enables the forecaster to obtain a more complete understanding of the three-dimensional structure of the wind field than he could get from the synoptic maps alone.

The isogons of primary interest are the 36 and 18 lines, representing the boundary between easterly and westerly winds. At many tropical stations the boundary between low-level trades and upper-level westerlies lies quasi-horizontally across the time-section chart most of the time. This boundary actually represents the intersection of the major anti-cyclonic ridge line with the plane of the time-section. It changes height from day to day and frequently shows a sharp downward dip during the passage of an upper-level trough in the westerlies. The depth of the easterlies is a significant feature of the synoptic situation and may be associated with the cloud and weather distribution (section 6000.). The shear layer between the easterly and westerly currents is characterized by light variable winds. The thickness and height of this layer may be easily determined on the time-section. When the shear layer above an area is quasi-horizontal and occurs at a level corresponding to that of a horizontal wind chart, the forecaster may wish to outline the area and label it as an area of light, variable winds. His map analysis within this area is likely to be complex and unrepresentative. Therefore, he should examine his time-sections to select suitable higher or lower levels for analysis.

The 09 and 27 isogons are also useful, in conjunction with the 36 and 18, as a means of locating singular points in the wind field. As in horizontal wind analysis, the time-section isogons intersect in the singular points and the wind speed is zero at the intersection (Fig. 4-40). The singular points which appear on the time-section represent the intersection of the sloping vertical axes of moving singularities in the horizontal wind field with the plane of the time-section. Whenever possible each singular point on the time-section should be identified with the corresponding singular points on the streamline charts. This process enables the forecaster to visualize the vertical continuity in his wind charts more easily. At times, the vertical axis of a singularity in the wind field may

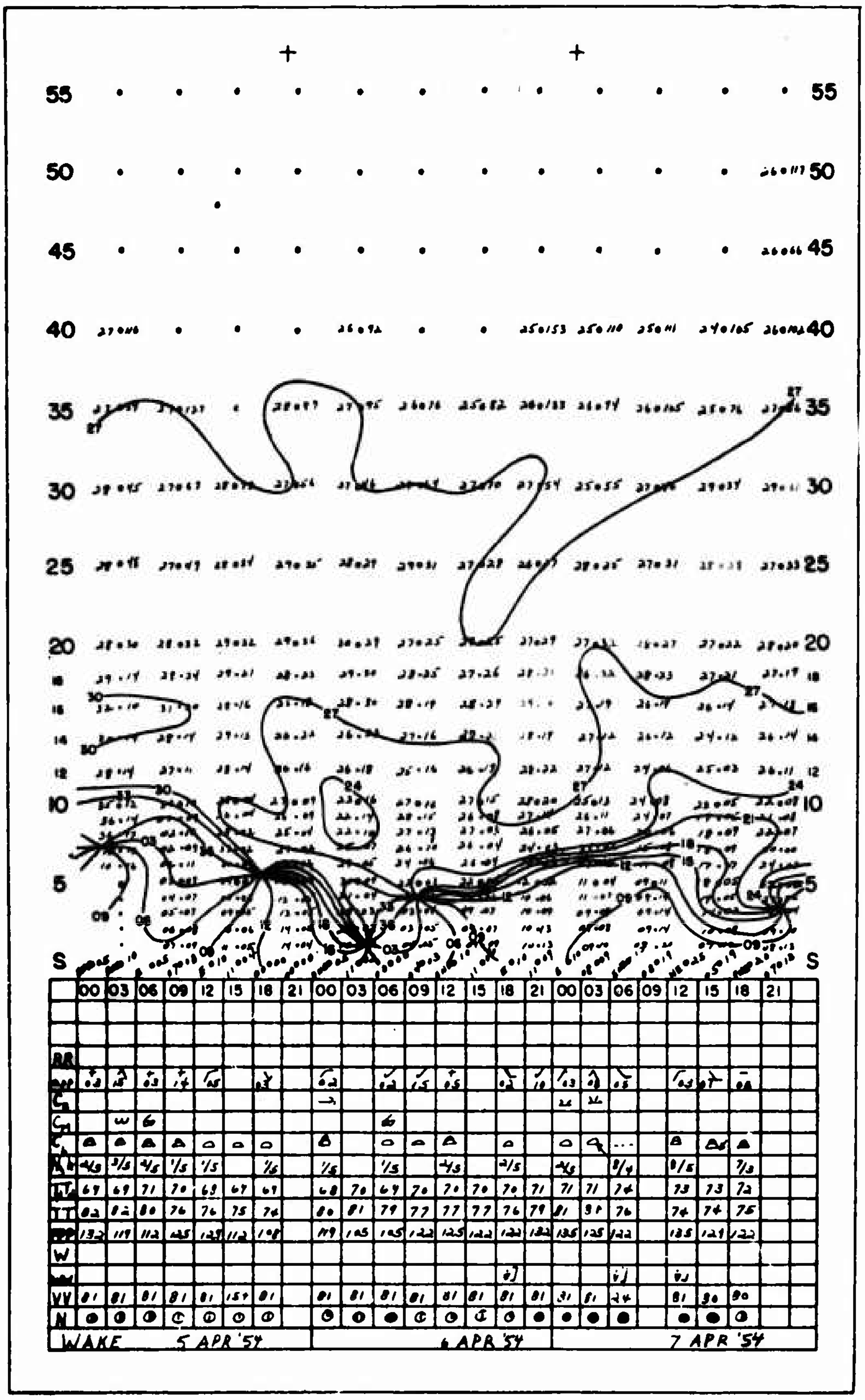


Fig. 4-40. Isogon analysis on a time-section, illustrating a shear layer and singular points.

have such a great slope that it approaches the horizontal. This is especially true of some neutral points. When such is the case, it becomes difficult to identify the singular points on the time-section with the corresponding singular points on the synoptic maps.

When a complete isogon analysis is used on the synoptic wind maps, a similar analysis on the time-section enables the forecaster to observe which isogons have moved past each station, at each level, during the time interval between maps. However, when used in conjunction with the direct method of streamline analysis, the time-section isogon analysis need consist of only the 36 and 18 lines, plus short segments of the 09 and 27 isogons where they intersect the 36 and 18. This sketchy analysis is sufficient to indicate the separation between the major easterly and westerly wind currents and to fix the location of the singular points.

4612. Analyzing the Turning of the Wind. At any given station, turning of the wind with time is frequently associated with the passage of waves in the wind currents. Assuming that the waves are moving past a station in the direction of flow, veering (clockwise turning) of the wind, in the Northern Hemisphere, is associated with the passage of the cyclonic part of the waves and backing (counterclockwise turning) with the passage of the anticyclonic part of the wave. The opposite relationship exists in the Southern Hemisphere. Most perturbations in the wind currents move in the required manner. However in certain cases, such as a wave induced in an easterly current by a trough in overlying westerly flow, the movement may be opposite to the direction of flow in the easterlies. In such cases veering becomes associated with the anticyclonic part and backing with the cyclonic part of the wave. Changes in the amplitude or length of a wave can also cause veering or backing of the wind at surrounding stations, and the winds at a station may shift rapidly with the passage of a well-marked asymptote. Therefore, the turning of the wind must always be carefully interpreted in terms of the horizontal wind chart.

One convenient method of analyzing the turning of the winds on the time-section is to use colors to indicate the amount of veering or backing which has taken place in each twelve hour period. As each new wind sounding is plotted the amount of veering or backing, from the observation preceding it by twelve hours, is indicated by drawing a colored line between the plotted winds at each level. Red and orange may be used for veering of less than 45 degrees and more than 45 degrees respectively and blue and green for backing of less than and more than 45 degrees respectively. When observations are received at six hour intervals, the twelve hour periods for which the turning is evaluated will overlap on the time-section and the colored lines used to indicate the turning must be placed under each intermediate observation.

As the turning of the wind changes from veering to backing and back to veering the colors vary across the time-section. Inflection lines may be drawn between the areas representing either type of turning. By noting the time which an inflection line passes a station, at a given level, and estimating the rate of movement of the corresponding inflection line in the streamlines for that level, the forecaster can determine the position of the inflection line relative to the station on his streamline chart.

Lines corresponding to the wave axes, or trough and ridge lines, may also be drawn on the time-section. These will be drawn through the points of maximum

4612.

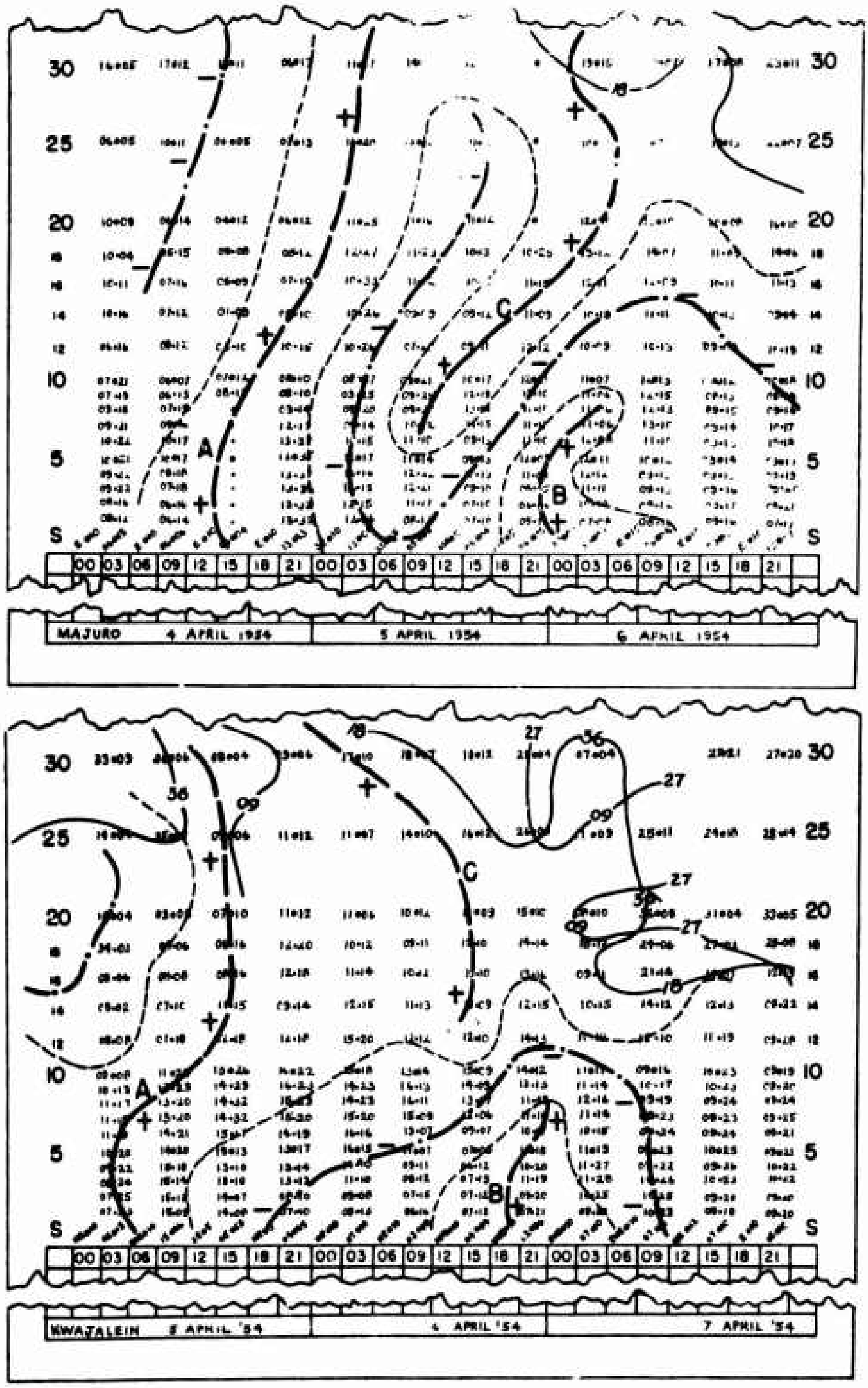


Fig. 4-41. Time-sections, showing the passage of waves in the easterlies at Majuro, above, and Kwajalein, below. ——— axis of maximum veering. —·—· axis of maximum backing. ----- inflection lines. ——— isogons for cardinal directions. + indicates turning associated with cyclonically curved streamlines. — indicates turning associated with anticyclonically curved streamlines.

turning at each level and will naturally fall between the inflection lines. When the rate of turning is relatively constant during any period of veering or backing, the wave axis lines are drawn through the center of the area between the inflection lines on either side. The lines representing the axes of maximum veering may be colored red and those representing maximum backing may be colored blue. After examining the streamline charts to determine the relation of the turning of the wind to the synoptic wind patterns, each axis of veering or backing, on the time-section, should be labeled with positive or negative signs, indicating whether the turning of the wind is associated with the movement of cyclonically or anticyclonically curved streamlines respectively. The time of passage of the wave axes at each level may then be determined readily from the time section and the information used to help locate the corresponding wave axes on the streamline charts. The wave axes located in this manner represent the axes of sharpest curvature in the streamlines and need not be oriented normal to the wind current.

When one or more stations are located upwind from a station for which a forecast is required, waves observed passing the upwind stations may be anticipated at the downwind station. For example, in the upper diagram of figure 4-41 the cyclonic axes of a well-marked wave (A) and a weak wave (B) are seen passing Majuro, in the low-level winds. In the lower diagram of figure 4-41 the cyclonic axes of these same waves may be seen passing Kwajalein about 36 hours after passing Majuro. Kwajalein is located approximately 250 nautical miles west-northwest of Majuro.

Wave (A) extends vertically to at least 25,000 feet at both stations, while wave (B) extends to only 10,000 feet at Majuro and 8,000 feet at Kwajalein. There is a third wave (C) which affects only the winds between 6,000 feet and 25,000 feet at Majuro and only those between 10,000 feet and 30,000 feet at Kwajalein. The 10,000 foot level at Majuro is affected by all three waves. The 10,000 foot synoptic wind chart would therefore be complicated by three waves while charts for higher and lower levels would indicate only two. The time-section then becomes an important tool for establishing the correct vertical continuity.

4613. Analyzing the Wind Speeds. At some stations in the trade wind zone variations in cloud and precipitation are associated not so much with changes in wind direction as with variations in the speed of the easterly current. It is advisable in such cases to carry out not an isogon, but a speed field analysis. Isotachs at 5 knot or 10 knot intervals are drawn on the chart exactly as if it were an ordinary horizontal map (Fig. 4-42). The main object of this analysis is to detect the passage of maxima and minima in the wind speed and to discover at what levels these maxima and minima are found. A complete analysis, of course, consists of both the isogonal and the speed patterns superimposed upon the same form. There is usually no difficulty in making a clear, easily read single station analysis of this type if the base form is printed lightly, say in orange, and the plotting of the data is done neatly with small figures.

4614. Analyzing the Depth of the Moist Layer. The time-section form also provides a convenient means of recording the depth of the moist layer. The top of the moist layer is determined from the radiosonde data and marked on the time-section at the appropriate grid point. The plotted points are then connected by a colored line to provide a continuous trace of the changes

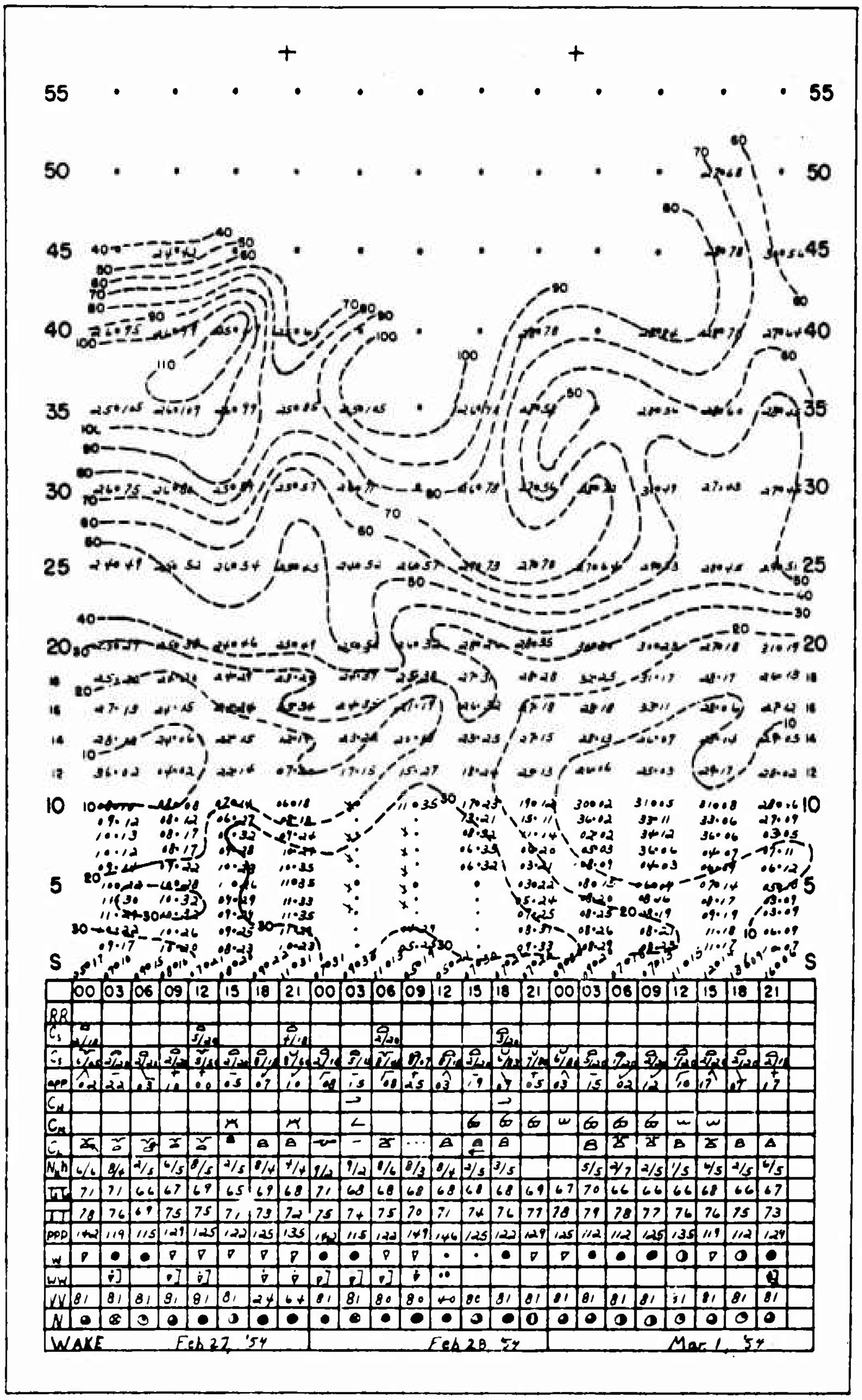


Fig. 4-42. A time section illustrating isotach analysis.

in height of the upper limit of the moist air.

4620. The Route Strip-Map.

Another important analytic and forecasting aid is the route strip-map. This is a small map of the area within a short distance on either side of a given flight route. It is used as a means of classifying, displaying and analyzing the data from in-flight weather reports. When the number of flights over a given route is limited to one or two per day, the in-flight weather reports, from the route, may be processed conveniently on the upper air synoptic maps. However, when there are numerous flights each day over any of the routes within his area of interest, the forecaster needs a more practical means of using the in-flight weather reports. If data from numerous flights at slightly differing times and altitudes over the same route are plotted on a single synoptic map, they tend to appear as a disorganized hodge-podge. Many reports often appear to contradict others, and the data from an individual flight are difficult to identify. In contrast, when the data from each flight are plotted on a separate strip-map, it may be interpreted and analyzed easily and is well displayed for use in debriefing incoming crews.

The wind data on the strip-maps may be analyzed easily by using the latest analyzed wind map, for a level near the flight level, as a guide. The strip-maps should be of the same scale and projection as the base map used for the wind analysis and should be printed on semi-transparent paper. Each strip-map then may be placed over its corresponding area on the latest wind map and the underlying analysis used as a guide in sketching an analysis on the strip-map. The analyzed strip-maps will serve as a guide in analyzing later synoptic wind maps. When the important features of the wind patterns have been located on the strip-maps they may be transferred directly to the synoptic charts, thus eliminating the need to plot in-flight weather reports on the latter.

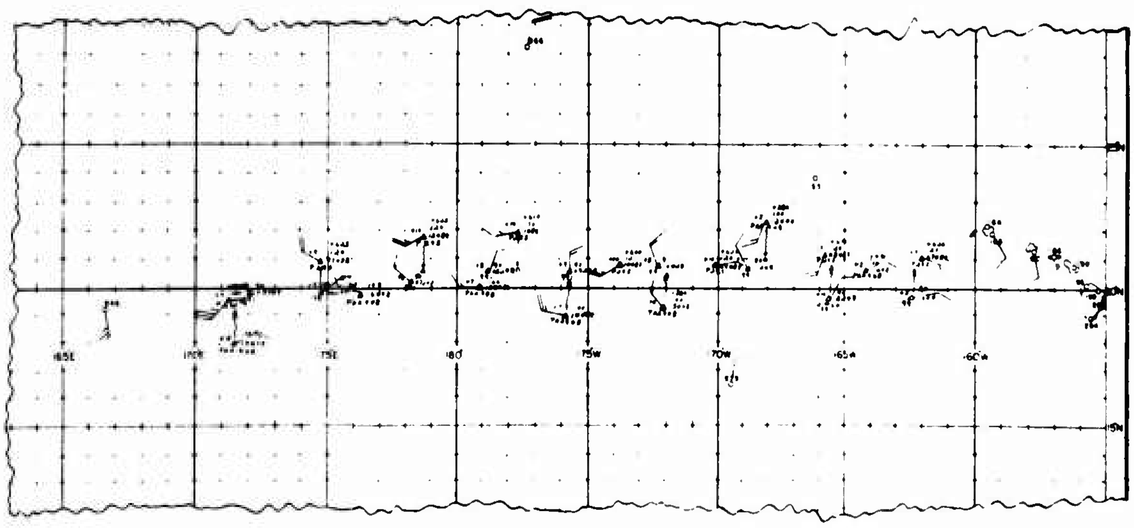


Fig. 4-43. In-flight weather reports plotted on a synoptic chart. Note the apparent conflict in the data.

Figure 4-43 illustrates a 10,000 foot chart with plotted data from three flights on the route between Hickam Air Force Base, T.H., and Wake Island. The

4620.

flight levels are at 9,000, 10,000 and 12,000 feet. Notice that, even in areas where there is little time difference in the observations, many of the reported winds appear to be in disagreement. In figure 4-44, we see the data from these same flights plotted on individual strip-maps. Reported navigation

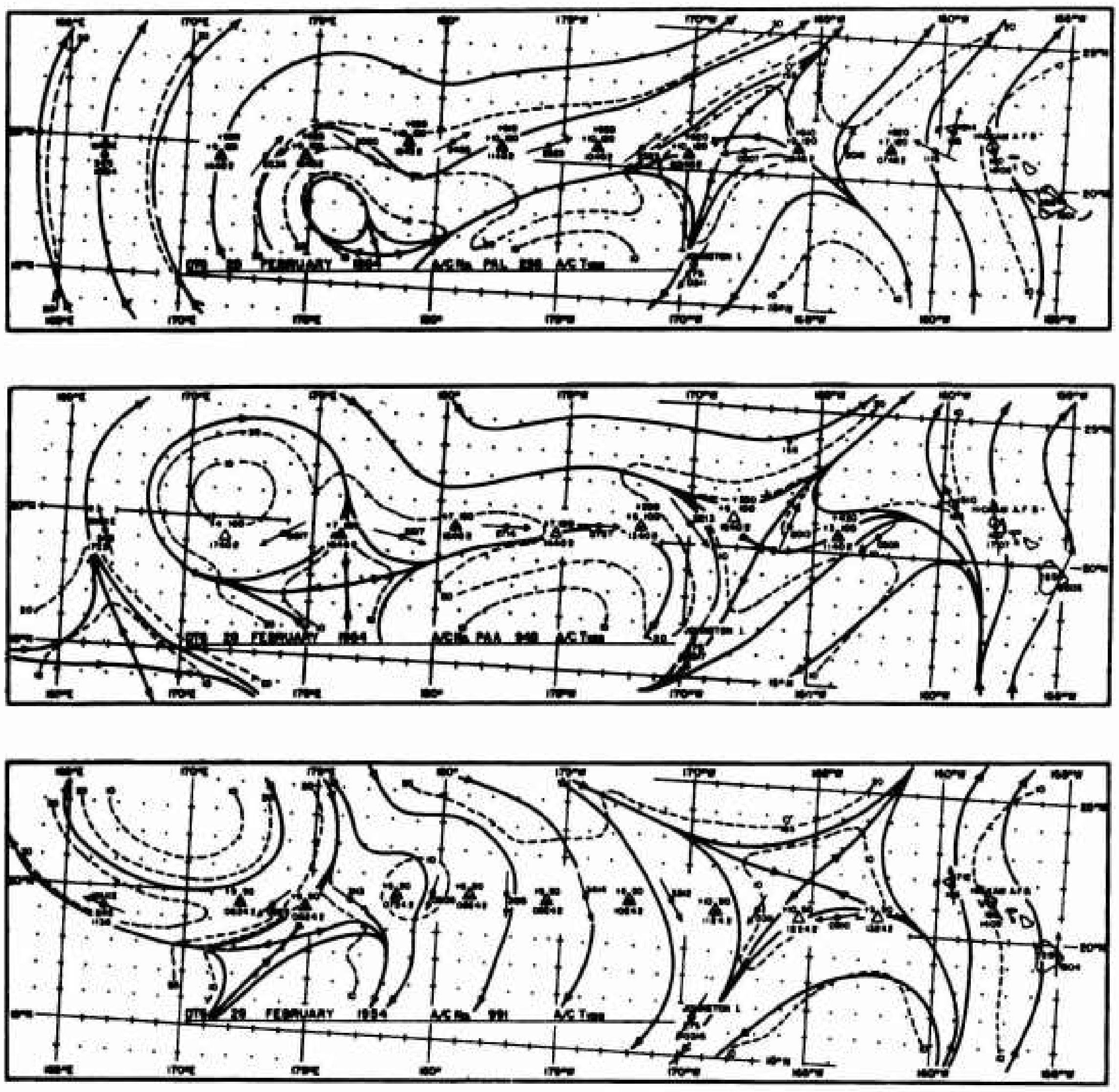


Fig. 4-44. In-flight weather reports plotted on strip-maps. Note the vertical and time continuity in the three analyses.

winds are plotted between the appropriate reporting positions. A rough wind analysis has been sketched on each map; this analysis is consistent with each wind observation.

The patterns in this example are not simple. When the reports from all three flights are plotted together, as in figure 4-43, analysis is almost impossible. Certainly, winds within a three-thousand foot layer do not always disagree as much as these. Occasionally, however, the disagreement is even

more marked, and for good reason. Wherever the axes of ridge lines and trough lines slope steeply and intersect the flight route, the winds only a few hundred feet above and below the intersection will be in apparent disagreement. In this example, the southward slope of the ridge line coincides with the flight route at approximately 9,000 feet. As a result, the 9,000 foot flight (the lower strip-map, figure 4-44) has a preponderance of variable, but predominantly northerly winds. The central portion of the 10,000 foot flight route (the middle map of figure 4-44) is north of the ridge line, at that level, and encounters predominantly westerly winds. The central and western portions of the 12,000 foot flight are decidedly north of the ridge line at the 12,000 foot level; as a result, the 12,000 foot strip-map shows fairly strong south-westerly winds.

This description certainly over-simplifies the wind patterns in figure 4-44; the location of neutral points also introduces deviations in the wind. Nevertheless, these flights do show how the sloping axis of a major synoptic system can disturb the wind patterns within a relatively thin layer.

The reader must realize that the strip-maps are not synoptic, i.e., they represent conditions encountered over an eight to ten-hour flight. Therefore, they must be used only as an adjunct to the synoptic map. In transferring any feature from the strip-map to the synoptic map, allowance must be made for the time-movement of the feature (see Section 4430).

One useful feature of the strip-map is that it permits smaller scale maps to be used. Since only a small amount of data is plotted on each strip-map, they may be of relatively small scale. Also, since the consistent use of the strip-maps eliminates the necessity of plotting these inflight reports on the horizontal wind charts, a smaller scale may be used on these latter maps. We repeat, however, that the scale on the strip-maps and the horizontal wind charts must be the same. Any scale smaller than 1:20,000,000 is inadequate for either chart.

The most important feature of the strip-map is that it enables the analyst to use data which might otherwise appear conflicting and worthless.

5000. ANALYSIS OF THE FIELD OF COMPOSITION.

5100. COMPOSITION OF THE TROPICAL ATMOSPHERE.

Many years ago it was established that the major constituents of the atmosphere, oxygen and nitrogen, varied insignificantly in amount from place to place at the earth's surface. The physicists of the time still assumed, however, that in the vertical a separation of the gases of the atmosphere into lighter and heavier elements would occur. They presumed that hydrodgen and helium would be found to predominate in the upper atmosphere. Recent research has shown that this expectation is not fulfilled. At least so far as its major constituents are concerned, the composition of the atmosphere varies very little below 200,000 feet and the only plausible explanation of this fact is that mixing is sufficiently intense both among the upper layers of the atmosphere and between those regions and the troposphere to assure approximately uniform composition. The same state of affairs is found when the very rare gases of the atmosphere, such as argon, xenon and neon, are studied. The proportion of these rare gases in the air varies very little from place to place. To find the more variable constituents, therefore, we must look at the substances which are not as abundant as oxygen and nitrogen nor as rare as the noble gases. First, we have solid and liquid particles swept up from the surface of the earth by the activity of the wind: desert and industrial dust, smokes, salt particles from the spray of the sea etc. Second, the amount of carbon dioxide varies from place to place and, as a result of industrial activity, has tended to increase in the atmosphere during the past 100 years. Lastly, we have the major constituent of interest to the meteorologist -- water substance. The percentage variation of water substance in the atmosphere, when regarded as a variation of the total material constituting the envelope of the earth, is insignificant; but when considered in relation to its geophysical effects it is by far the most important meteorological variable affecting life on the earth. This is partly because water substance is the only important natural constituent of the atmosphere which, at the temperatures encountered on the planet, can exist in each of its three phases, vapor, liquid and solid. Changes of phase, that is, transitions from vapor to liquid water or to ice and vice versa, which take place chiefly in the troposphere, produce the variations in cloud and precipitation which we call the weather.

When a meteorologist speaks of the analysis of the field of composition, then, he usually has in mind the delineation of the changes in the state of water substance, more particularly the changes from vapor to liquid and solid and the precipitation of the latter on to the surface of the earth. Nevertheless, a complete analysis of the field of composition would include not only changes in cloud and precipitation but also the delineation of changes in distribution of water vapor, both in the horizontal and the vertical, and the graphical depiction of the concentration of industrial and natural smokes and dusts, salt particles, and similar pollutants. Variation in the amount of carbon dioxide in the atmosphere has not yet been found to be of profound importance in meteorology and it is consequently omitted in the analysis of the field of composition. As a result of post war nuclear developments the variation in concentration of radioactive isotopes

is also to be regarded as falling within the field of meteorology. However, the study of these changes is a highly specialized function, regarded at present as being beyond the scope of the normal weather station; it also is omitted in the discussion.

In oceanic tropical meteorology the only variations of composition not involving water substance that are important in air operations are those due to the activity of volcanos, the presence of smoke from forest fires, and the presence of sea spray and salt haze over the open sea under special conditions. Since all these variations are passive, that is, depend on dispersion of material by turbulence and the prevailing winds, a good wind analysis and forecast will lead to a sufficiently accurate estimate of their effect on operations. The dust storms of certain tropical continental regions are passive phenomena and can be treated similarly. Here we shall treat the active changes -- that is, changes involving variation of phase and transformation of energy such as occurs during cloud formation. From this point of view, the chief problem of the analysis of the field of composition is the problem of cloud and precipitation analysis.

5200. The Classification of Tropical Clouds.

There is no essential qualitative difference between the clouds of the torrid zone and those of higher latitudes. The international system of classification of clouds, developed almost entirely from the study of temperate and arctic hydrometeors, is still applicable in tropical meteorology.

Nevertheless, the frequency of occurrence of the various species of clouds is quite different in low latitudes -- certain forms considered relatively unimportant by the synoptic meteorologist working in continental middle latitudes become the predominent cloud species of the tropics. Similarly other cloud forms whose varieties are reported minutely in the international cloud reporting code, because of their significance in frontal and air mass analysis, are relatively unimportant or even rare in low latitudes. For this reason the international cloud reporting code is inadequate in some respects and too lavish in others in its use of the code numbers. The same remarks might be applied to the classification of precipitation types in the weather reporting code. However, these deficiencies and excesses of the surface reporting code can be compensated by a close study of aircraft reports, particularly those from weather reconnaissance aircraft. In the interpretation of these reports, a detailed knowledge of the classification of cumuliform clouds becomes necessary.

While all the species of clouds, as recognized in the international classification, are found both over the land and over the sea in the tropics, the analyst must always be careful to keep the distinction between orographic and oceanic cloud in mind. At a large distance from large or mountainous land masses, say more than 100 miles, diurnal variation in all types of cloud seems to be very small. There have been frequent reports that there is some diurnal cloud variation over the open sea but this variation is so small as to be relatively unimportant in synoptic analysis. On the other hand, over tropical mountainous islands and the neighboring sea and over the continents, the diurnal cycle of convection is extreme, and neither adequate analysis nor correct forecasting can be carried out unless the distinction between orographic and oceanic

cloud is continually maintained in the analysis. The discussion of tropical clouds, then, appropriately begins with oceanic clouds, since these show so little diurnal variation. First, a broad general introduction to the subject may be established by the study of climatological charts showing the distribution of the various cloud species. In section 2300, the distribution of the various types of low, middle and high clouds appear in diagramatic form. The maps displayed there show immediately that the predominating cloud form of the tropics is cumulus. The tropical meteorologist therefore first needs a finer classification of convective cloud, especially cumulus, than has been necessary in the past. Four major types of convective clouds: cumulus-humulis, cumulus-mediocris, cumulus-congestus, and cumulonimbus are recognized in the International Classification; they are further subdivided here. Secondly, certain clouds of the high atmosphere, which in middle latitudes appear in regular succession and which consequently have dominated the classification of cirriform types, are rare or absent in the tropics or occur in successions which are not found in other zones; consequently the high clouds also require a new treatment. Thirdly, since the majority of hydrometeors of operational interest are found in the troposphere, and since the height of the tropopause in low latitudes is much greater than that elsewhere, the height ranges over which the classification into lower, middle and upper clouds extend are much greater. For example it is not at all rare in subequatorial regions to find altocumulus, consisting of water drops, at 30,000 feet. Cirrus may be as high as 60,000 feet and the vertical extent of some convective clouds is as great -- cumulonimbi which reach from 500 to 50,000 feet are not uncommon in the Western Pacific. While these differences between high and low latitude weather are important enough, there is another of far greater significance. For some time tropical meteorologist have known that the precipitation of clouds in low latitudes differs markedly from that found poleward of the anticyclonic belt. In the tropical easterlies rain falls from quasi-horizontal sheets of altostratus and from cumulus when both types are entirely below the freezing level and consequently contain no ice. In higher latitudes on the other hand precipitation falls chiefly from sloping sheets of altostratus clouds associated with warm fronts, and from cumulonimbi; it has been accepted that, unless both types of clouds have an admixture of ice, the precipitation from them is negligible. The Bergeron-Findeisen theory of precipitation, until recently almost unquestioned, is based on this observation. The great difference between precipitation in the easterly and westerly branches of the general circulation makes both the analysis and the forecasting of the field of composition more difficult in the tropics.

The subdivision of the categories of convective cloud follows the broad classification of high latitudes, which is made according to the presence or absence of visible ice veils on the cloud. When no ice is visible the hydrometeor is identified as cumulus mediocris, if its thickness is close to the mean for the season and latitude, cumulus-humulis, and cumulus-congestus, if it is below or above that mean, respectively. If an ice veil is present, the cloud is a cumulonimbus.

The most striking variation among cumuli and cumulonimbi is the extent of lean, or shear, of the cloud, that is, in position of the main axis of the cloud with respect to the vertical. In general, we can divide the convective clouds, whether or not they have ice veils in their tops, into the doldrum class, where lean or shear is small or absent, and the trade class, where

the shear is sufficiently marked to be immediately obvious to eye examination. A second distinction among cumuli and cumulonimbi may be made according to the arrangement of the clouds with respect to one another. On some occasions the clouds are isolated from one another -- each seems to be developing independently of its neighbors -- if this is the case, the cloud is classified as isolated. More frequently, however, the convective cloud elements show arrangement and orientation. Either they tend to form small groups, perhaps dominated by a central member, or they are arranged in lines bearing some resemblence to the fronts of high latitudes. The grouped or oriented clouds are said to belong to the category: family type. There are therefore four chief subclasses of convective cloud: isolated doldrum, family doldrum, isolated trade, and family trade. When these categories have been applied to the three types of cumulus and to cumulonimbus, and the presence or absence of large amounts of fracto-cumulus has been noted, sufficient subdivisions of convective cloud have been achieved for practical purposes.

In some situations it would be desirable if the presence of altocumulus, altostratus, or stratocumulus, known to be derived from the convective cloud pillars, could also be reported. Middle and upper clouds could then be classified according to their relation to convective clouds. Stratocumulus, altocumulus altostratus, and cirrus all may be formed either from the convective pillars themselves (dependent type) or independently. The distinction between dependent and independent types is very important in the analysis of the weather distribution chart and if the distinction could be made in weather reporting, the work of the analyst would be much simplified. Where the distinction is not made, analytic judgement in interpreting the standard cloud reports becomes necessary. The following description of the specific cloud types provides some means by which this judgement may be exercised.

Over the open sea, by far the most common height for the base of convective cloud is 2,000 feet. This base will frequently lower to 1500 and occasionally to 1,000 feet in precipitation. Lowering in precipitation is more pronounced with cumulonimbus and bases of these clouds often occur at 500 feet over the open ocean. From the weather reconnaisance data or from Pomars important cloud dimensions may be derived--; the height of the tops, the height of the base, the shape of the cloud, and whether it is precipitating or not. Additional information which would be of the greatest use in analysis but which at present is reported neither in the international cloud code nor by reconnaissance aircraft would be the extent of lean or shear in the cloud, the effective cloud thickness (abbreviated ECT and more fully described below), the horizontal dimensions of the top and bases of representative individual clouds and whether precipitation is falling from the top and sides of the cloud as well as from the base.

In connection with the study of cumulus precipitation, some refinement in description is necessary. There have been statements that cumuli of very small vertical dimensions precipitate over the open sea. Experience in the Marshall Islands indicates that these reports are probably based upon a misapprehension. If the top of a cumulus cloud is detached from its base at the moment of maximum vertical development, just before rain from the cumulus is due to occur, precipitation may fall from the detached top and not from the base. If the observer has not carefully watched the previous

development of the cloud he may suppose that the top is, itself, a complete cloud. When the proper distinctions are made it is possible to estimate the minimum thickness of a cumulus cloud which will give precipitation: this minimum effective cloud thickness is about 6,000 feet.

The major points already outlined may be illustrated by reference to specific cloud types over the open ocean.

5210. Doldrum Cumulus.

Extensive regions over which very light winds or calms prevail are common near the equator in the western parts of the oceans. Unlike the calm areas accompanying the centers of the oceanic high pressure belts, such "doldrum" areas are characterized by wide spread and heavy precipitation. While much of this rain, perhaps the major portion by volume, falls from altostratus and from cumulonimbi, the most frequent showers are precipitated from doldrum cumuli which do not attain the levels at which ice may form. The peculiarities of these cumuli depend not only on the light winds of the doldrums -- the wind must also vary only slightly with height in either direction or speed over the levels through which the shower clouds extend. The typical isolated doldrum cumulus has a vertical axis. The base is slightly wider than the top; it is followed by a narrow "neck" which may often have a very smooth outline; the top is bulging and well rounded, usually consisting of a single "cauliflower lobe". Only occasionally are there associated slender stratocumulus strips, and when these occur there are often two preferred levels of formation: the first just above the base and the second at about the widest part of the top. The most frequent level for the base is 2,000 feet with a lowering at most to 1500 feet when the shower forms. The tops at maximum development vary between 6,000 and 12,000 feet with the most frequent height under calm conditions being at about 9,000 feet. With tops at this level the base diameter will be of the order of 3,000 feet, the broadest part of the top being somewhere near 2,000 feet across. The average time from the first appearance of the cloud until rain falls, after maximum development, is half an hour.

Fig. 5-1. Doldrum cumulus.

The isolated doldrum cumulus is a comparatively rare cloud; the almost dead calm extending from the surface to 10,000 feet, which is required for its perfect development, occurs very infrequently over the open ocean even in the regions customarily considered by climatologists to be the doldrums. More frequently a light wind of between 5 and 10 knots prevails in those regions, but this wind often will have little variation with height below 15,000 feet. Under these circumstances the doldrum cumuli will be arranged in groups or lines. The grouped clouds have a curious tendency to consist of

Fig. 5-2. Doldrum cumulus, precipitating.

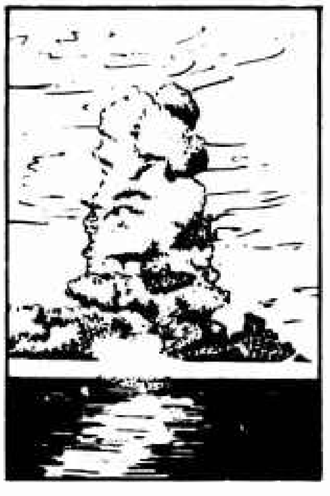


Fig. 5-3. Isolated doldrum cumulus.

three clouds of about the same stage of development, sometimes so closely approximating as to be fused at the base. When lines of doldrum cumuli form, they seem always to be oriented along the wind. Figures 5-1 to 5-3 illustrate these cloud types.

Figure 5-1 shows a portion of a line of doldrum cumuli in various stages of development, the central cloud being a family of three at about maximum development. One member of this group is precipitating. The correlated wind field, observed by rawinsonde at the time of the photograph from which this drawing was made, shows the absence of shear. The presence of large water drops in the precipitation from this cloud type is shown by the rainbow in figure 5-2. An isolated doldrum cumulus may be seen in figure 5-3.

5220. Trade Cumulus.

As its name implies, the trade cumulus cloud is most frequently found in the wind belt between latitudes 10° and 30° north and south of the equator. It is not confined to these regions; wherever the appropriate wind and stability conditions exist, even on the equator, trade cumulus will be found. Its chief characteristic is that the axis of the cloud mass is inclined. Both isolated and family types of orientation of the individual cloud elements are equally common. Occasionally, linear arrangements are encountered, with the lines as much as 300 miles long. Even isolated cumuli tend to adopt a linear arrangement. This may not be evident until the clouds are observed from some height, such as above 25,000 feet.

Trade cumuli vary widely in their dimensions. The base usually is near 1,800 feet; under conditions of strong horizontal velocity divergence (see Section 6200) in the lower atmosphere, small amounts of trade cumuli may be based as high as 3,000 feet. The height of the tops varies both with latitude and longitude in step with the geographical variation of the atmospheric stability, as shown by the radio soundings. For example, the characteristic height of the trade cumulus tops in the Eastern Pacific is 7,000 feet. Further west, from the Marshalls to the Philippines, the most frequent height of the tops will be somewhere between 7,000 and 10,000 feet. On the average, the tops will be higher the lower the latitude, but this is not invariably the case, since certain equatorial regions are noted for

their dryness and stability aloft. Thus, the equatorial portions of the Central Pacific, north of the Marquesas Islands, are very dry and are characterized by trade cumulus clouds not more than 4,000 feet thick. The horizontal dimensions are more difficult to estimate, since the form of the cloud depends so much upon the vertical wind profile. Typical basal diameters lie between 3,000 and 4,000 feet; if the shear in the wind is extreme, the tops may be considerably larger than the bases, streaming out to as much as 6,000 or 7,000 feet along a longitudinal axis. Small isolated trade cumuli have a typical basal dimension of 1,000 feet with the tops much narrower than that.

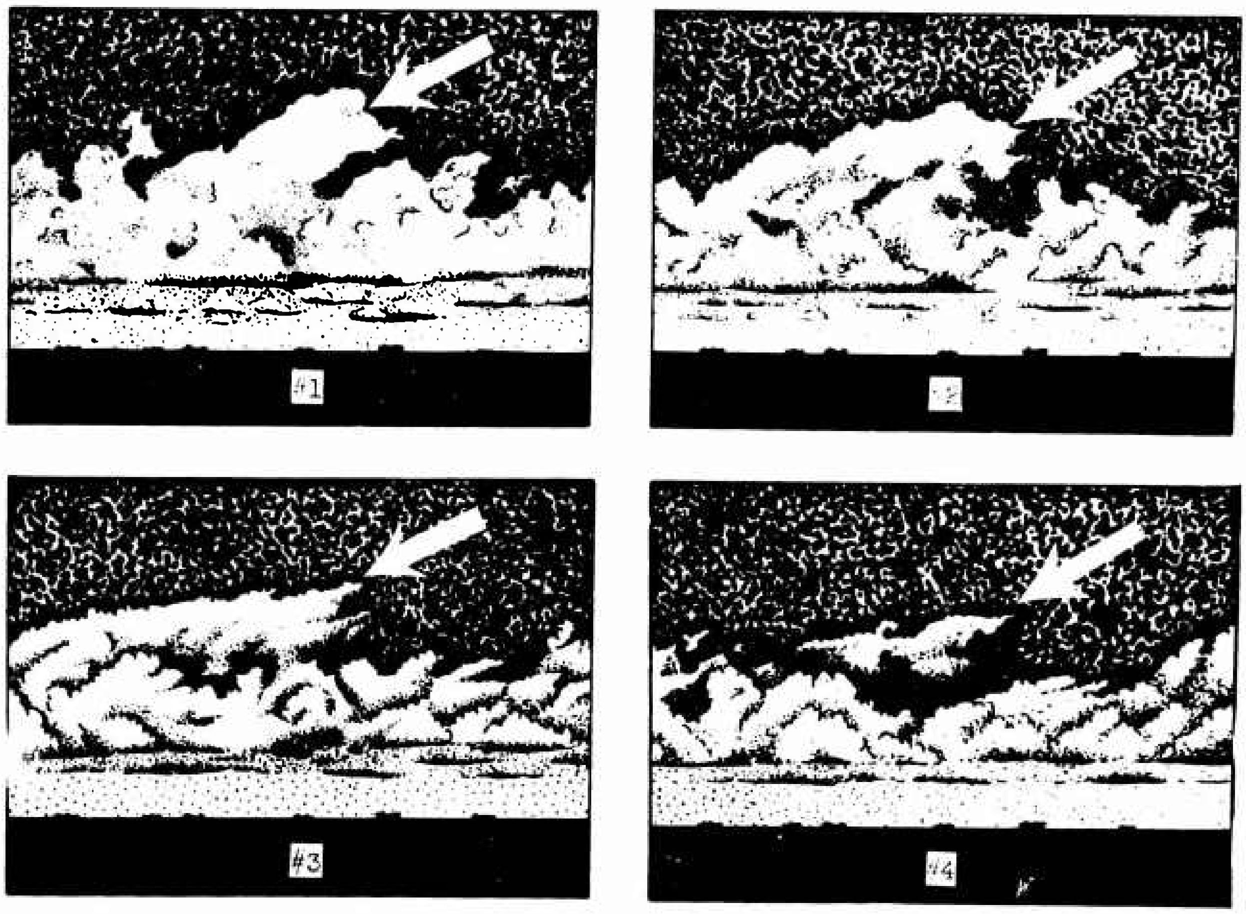


Fig. 5-4. Trade cumulus sequence, showing "shearing" of the upper part of the cloud. (From photographs taken at two-minute intervals).

Figure 5-4 illustrates the motion and development of an extreme form of trade cumulus. The wind soundings for the day showed that the vertical shear in the wind was very great. The photographs from which the drawings were made were taken at two-minute intervals, and they illustrate the inclination of the clouds and the destruction of the tops. During the shearing of the upper part of the cloud, the tops approximate to stratocumuli and are frequently so reported in routine weather observations.

The most important cloud parameter, however, is the effective cloud thickness. This may be defined as the distance between the center of the base of the

cloud and the highest point on the cloud surface vertically above that point. If the shear in the cloud is extreme, this effective cloud thickness may be smaller than the depth of the cloud measured vertically from top to base. Unfortunately, routine weather reports give only the height of the tops and the bases of the clouds and no estimate of the effective cloud thickness. The importance of this parameter depends on the fact that, if the shear of the cloud is sufficiently great to be easily recognized by eye observation, trade cumulus is unlikely to be accompanied by precipitation.

Experience in the Pacific suggests that the effective cloud thickness over the open sea must be at least 6,000 feet before traces of precipitation from the base can be seen. This is a necessary, but not a sufficient, condition; it appears that the effective cloud thickness can sometimes be greater than this without precipitation.

Stratocumulus may or may not be associated with trade cumulus. It is common to find small fragments associated with the base at approximately 500 feet above the lifting condensation level. Occasionally, large amounts of stratocumulus may be formed by a "streaming" of the tops under great shear.

5230. Fracto-cumulus and Fracto-stratus.

Napier Shaw (1926) has raised pertinent objections to the prefix "fracto" in cloud classification. He says, "There is at present no general international agreement as to the physical processes which are presented by the several cloud forms. I should find it very difficult to reconcile the adjectives ventosus or fractus, for example, with the views of the physical processes which seem to me to be established: in the case of ventosus because it suggests a relation between a form of the cloud and variations of the wind for which we have no evidence, and in the case of fractus because it suggests, equally without evidence, that the separated clouds were originally united". Oceanic observations seem to establish that the clouds ordinarily classified by observers as fracto-cumulus or fracto-stratus originate in several distinct and unrelated ways:

As the initial stage of cumulus or stratocumulus cloud. Since cumulus, at least, passes rapidly toward its maximum development soon after initial formation, the cloud form predominating at any time will approximate to the form at maximum development. The initial stages, if isolated, will appear as insignificant cumulus-humulis or fracto-cumulus interspersed among the larger clouds. If the cumuli grow more slowly than normal, large amounts of fracto-cumuli may be reported; they may then be taken as evidence of strong shear which will not prevail.

As true fracto-cumulus, that is, cumulus fragments usually sheared from the parent cloud. From the ground, the base of such fragments may appear to be at the same level as the rest of the cumuli, whereas, when they are observed from the air, they will seem to be at the general level of the tops.

As very small pieces of the stratocumulus which frequently form as thin sheets or plates just above the base or below the top of the cumulus. In some of these cases, the stratocumulus has no connection at any time with other clouds.

As aborted cumulus. Occasionally, especially when the lower atmosphere is stable and the wind shear very strong, the initial stages of

cumuli are short-lived. Turbulent motions can be detected in the cloud at the moment of its formation, and the cloud itself rapidly thins and disperses in the form of filaments, usually curved, which evaporate. The sky may contain as much as 5/10ths of such short-lived clouds. Observations at sea show that these fragments have a lifetime of the order of five minutes. They constantly form and disappear.

The term, "fracto-cumulus", has become established in the literature beyond revision. It is well to remember that as many as four distinct types of cloud may be included under this term. "Fracto-cumulus" is greatly over-used to report the types of clouds described above.

5240. Altocumulus and Stratocumulus Formed from Cumulus.

The process by which the tops of cumuli may shear off to form fracto-cumulus or stratocumulus has been described. If the cumulus cloud top is high enough, the dependent cloud will be classified as altocumulus rather than stratocumulus.

It is characteristic of this type of stratiform cloud that the rolls are longitudinal, that is, oriented along the wind. This is to be attributed to the manner in which they are formed. Since appreciable amounts of this cloud will be developed only when the parent cumuli are oriented in lines which lie along the wind, the derived stratocumulus or altocumulus will also show this characteristic.

5250. Independently Formed Stratocumulus.

Independent stratocumulus often appears, to superficial observation, to have originated from cumulus either by shearing off and spreading of the cumulus top or by spreading of material from its sides under an inversion. However, close observation, especially from an aircraft, of the steps by which the stratiform cloud develops will show that the elements originate in clear air as distinct entities unconnected with the cumulus. Later they may become fused with one another and with the cumulus.

In small amounts, stratocumulus of this type is very common between lines of oceanic cumulus-congestus. However, it is also found over the open ocean in areas from which cumulus is completely lacking; it then occurs in patches, each of which usually measures five to ten miles across. Outside this patch, cumulus may predominate, and there appears to be no reason why single patches of stratocumulus should persist in this manner. It is suspected that the patch first forms during precipitation from a group of large cumuli which disappear after rain; conclusive evidence on this point, however, is not available.

In the higher tropical latitudes, sheets of stratocumulus frequently form just below an inversion in the trades. Such sheets are often very extensive in the divergent area between the centers of the subtropical highs and the trade wind maximum. If cumulus is present, it is usually in the form of cumulus-humulis, unrelated to the stratocumulus and at a lower level. The stratocumulus usually exhibits a roll, or corrugated, structure. In all cases examined in the Central Pacific, the rolls were transverse, that is, oriented normal to the wind at cloud level. It appears from shipboard observations that the roll structure is present from the very beginning.

5260. Altocumulus and Altostratus of Independent Formation.

While occasionally the altocumulus and altostratus which occur independently of convective clouds exist as very small patches, by far the most important species is that which is found in the form of very extensive but broken sheets. The sheets sometimes cover areas many thousands of square miles in extent. However, they are rarely absolutely continuous as altostratus over such huge areas; here and there the sheet thins out, vanishes or is transformed into mixed altostratus-altocumulus. When the cloud reports are plotted on a synoptic map, it is seen that even these thinner portions are still part of the much larger, organized system. The thicker parts of the system consist of deep altostratus cloud from which a fine but steady precipitation usually falls. Since such extensive systems of altostratus-altocumulus are of great synoptic importance, and since their presence and transformations are so difficult to forecast in practice, they form the major topic of this section. For brevity, the whole altostratus-altocumulus sheet is called an "alto-system".

Alto-systems occur in two major forms. The first form is known as the typhoon cloud, since it is commonly associated with the central portions of a typhoon or hurricane. It consists of a bowl-shaped altostratus or nimbostratus cloud extending from the central portions of the storm, at the edge of the eye, across the atmosphere above and beyond the strong surface wind belt. Its outer edge is often frayed into altocumulus or patchy altostratus; sometimes it extends to the cirrus level, showing on its extreme outer edge a fibrous structure that indicates the presence of ice crystals. In the Western Pacific, the leading edge of the typhoon cloud is often remarkably well-defined and can be seen coming above the horizon as the typhoon approaches a station. Photographs from weather reconnaissance aircraft show that the alto-system is penetrated by cumulus and cumulonimbus, many of which pass through the sheet into the upper portion of the storm.

Though extensive, the typhoon cloud is not to be compared in horizontal dimensions with the second type of alto-system, the one which is associated with perturbations of the atmospheric layers between 20,000 and 50,000 feet. These are the sheets showing the greatest variation in structure. As already pointed out, part of the alto-system may be so thick as to constitute an overcast of nimbostratus from which light to moderate rain may fall. Near its edge, the sheet may thin out to form a deck of thin, plate-like altocumulus. Gaps, which are entirely free from middle cloud, may exist in the sheet. Not only does the sheet show this type of space-variation, but all of these various conditions may exist at a given station within a 24-hour period. At any individual station under the system, it is very dangerous to assume that, when such a sheet has cleared off, it will not return within the next 24 hours. Only the plotting of a weather distribution chart, and its analysis, can give the forecaster a guide to the space and time variations in the sheet. Once such sheets are formed, a process sometimes requiring several days, the system may be very persistent. Thus, in the Marshall Islands, cases are known in which an alto-system has covered the whole of the southern group of islands, from the Carolines to Majuro, for over a week. The correlations of this type of cloud with the upper-level synoptic situation are treated in section 6330.

5270. Precipitation from Stratiform Cloud.

As already remarked, precipitation in the tropics falls not only from cumulus and cumulonimbus but also from stratiform sheets; as far as any investigation has gone at present, it seems to fall only from stratiform clouds of independent formation. Sometimes, in the late stages of development of cumulus-congestus and cumulonimbus, originally independent stratiform clouds may fuse with a convective mass. Close observation during the rainout of this mass will show that the associated stratiform cloud is also precipitating. Under these circumstances, virga can be seen beneath a remarkably thin, associated, stratiform sheet. At the ground, this type of precipitation may not be distinguished from the rain that is falling from the cumulus or cumulonimbus. It is not possible, under the present reporting system, to make the necessary distinctions between the cumulus rain and the rain from the stratiform cloud.

5280. Cumulonimbus and Dependent Cirrus (Cirrus Spissatus).

Contrary to the usually accepted accounts of equatorial weather which appear in textbooks, cumulonimbus is not a common cloud over equatorial and sub-equatorial oceans. The climatic charts of the oceans, (see Section 2300) for example, show that less than 20% of the 1200 G.C.T. observations contained a report of cumulonimbus in the region between 10°N. and 10°S. and east of 160°E. The rarity of the cloud is more strikingly displayed, perhaps, by the low frequency of thunderstorms reported by all stations lying within this area. In general, from the Marshall Islands eastward, thunderstorms average about one a month.

Although cumulonimbus is a comparatively rare cloud, when it does occur over the ocean it is usually part of a linear convective system bearing a very close resemblance to the cold front of high latitudes. Such is the size of the tropical cumulonimbus and so massive is the convective activity of which it is an expression, that the presence of such a system can often be detected by synoptic analysis of the precipitation alone. It has often been remarked that the cumulonimbus is a veritable cloud factory. This is based upon the supposition that stratiform clouds in the neighborhood are outgrowths from it. However, these other forms are often expressions of widespread, organized convection in the upper air and hence would be regarded as independent. When this is the case, the line of cumulonimbus will be associated not only with parallel lines of cumulus-congestus of varying height but also with extensive sheets of independent altostratus and altocumulus. The associated alto-system may occur in as many as four or five layers, and the layers may, in part, fuse with one another and with the cumulonimbus. When well-developed, this alto-system also precipitates.

In spite of its huge vertical development, an individual cumulonimbus over the open ocean is comparatively short-lived. The entire development of an individual cloud rarely occupies a period of time longer than two hours. Toward the end of this period, the lower half of the cloud is dissipated by precipitation, leaving behind scattered portions of associated alto-clouds and the anvil top. Since the anvil almost always extends into regions where

the wind is different from the lower easterlies or lower monsoons, it becomes markedly asymmetrical. After the detachment, the asymmetry of the anvil becomes more pronounced, and it often stretches over a considerable horizontal distance. It begins to "fray" and disperse at the edges, probably under the action of turbulent eddies at the high levels to which it has penetrated. Nevertheless, it may persist in the upper atmosphere for a long time, almost invariably for several hours; it is suspected, under certain circumstances, that it may last as long as one or two days. During the latter part of this time, it is dispersed and distorted into strange forms. The main axis of the old anvil usually lies along the direction of the upper wind; in addition, the cloud forms lateral branches and filaments of very regular appearance, presumably because of the regularity of the eddies dispersing the cloud material. With the growth of large ice crystals in the cloud, precipitation trails may form and completely alter the original anvil appearance. In a late stage, a single anvil may extend as much as a hundred and fifty miles in the form of a filamentous "feather", or fish bone". All such forms should be classified as cirrus spissatus. In local forecasting, the meteorologist may often reconstruct a convective history of a locality for as long as the previous 24 hours on the basis of the knowledge of the usual transformations of anvils in the area and the various forms under which cirrus spissatus may occur. A knowledge of these forms is especially valuable to observers on weather reconnaissance aircraft.

5290. Independent Cirrus, Cirrostratus and Cirrocumulus.

In its early stages, cirrus spissatus is usually identified with ease. Later, it is distinguished from cirrus of independent formation with difficulty, particularly when occuring in small amounts. Independent cirrus is of synoptic importance only when it occurs as an extensive sheet of fibrous cirrus or cirrostratus. In sub-equatorial oceanic regions, extensive sheets of cirrus or cirrostratus of independent formation resemble independent alto-systems in that they are formed by large scale ascent associated with a synoptic disturbance in the high atmosphere. In fact, such cirrostratus sheets often precede the appearance of the alto-system by several days, and they may co-exist and fuse with such later developed sheets. The plotting of extensive independent sheets of cirrostratus and cirrus is often a valuable aid in the early detection of upper-level disturbances.

5300. THE WEATHER DISTRIBUTION MAP.

The weather distribution map is a graphical representation of the clouds and weather over an area of operation. In high latitudes, most forecasters would be reluctant to spend the time necessary for analyzing such a chart because the surface synoptic map, with the clouds and weather plotted at each station together with the identification of air masses and fronts, is adequate for most purposes. For operations in the tropics, however, the weather distribution map is almost indispensible for both forecasting and briefing. In instances where precise and detailed analysis of weather over particular terminals or areas is required, it is often necessary to follow the continuity of the weather and cloud patterns in the same fashion as the continuity of low pressure centers and fronts. As a briefing chart, the weather distribution map is perhaps the most practical means of presenting the weather to non-meteorologists. Finally, the art of forecasting the weather depends upon the ability

to correlate changes in the wind patterns with parallel changes in the cloud and precipitation patterns.

Several techniques of drawing a weather distribution map have been developed. The method outlined here is based upon one that appeared in the AAF Manual 105-10 (Tropical Meteorology, May 1945). It is, perhaps, the most practical solution to the problem of graphical representation of such complex variables as clouds and weather.

GGggZ - Time of observation (if off time)
w - Present weather
m - Remarks on present weather
W - Past weather
M - Remarks on past weather
f_c - Flight conditions
$Q_N Q_E Q_S Q_W$ - Quadrant weather
$N_1 N_2 N_3$ - Amount of cloud (in eights)
C - Type of cloud
hh - Base of cloud
HH - Top of cloud
W_s - Significant weather changes
S_s - Distance from occurence of W_s
W_c - Weather off course
D_w - Bearing to W
(AWS Manual 105-34, "Recco Code" dated 1 August 1953, will be used to decode the above elements)

Fig. 5-5. Plotting model for "Recco Code".

5310. Plotting Procedures.

The preparation of the weather distribution map is based on information from one or more of the following sources; (1) surface reports from land stations and ships, (2) reconnaissance aircraft reports (recco reports), and (3) transient aircraft reports.

The complete weather distribution plotting model is shown in figure 5-5. It is sufficiently detailed to enable all the data from a reconnaissance aircraft report to be plotted. A sample report from a reconnaissance observation is shown, both in code and in plotted form, in figure 5-6, below.

The present practice of taking the reconnaissance observations 100 miles apart limits the scale of the chart. If

EXAMPLE OF DATA

VULTURE LIMA

96669 04154 71248 61344

01501 03035 81902 24443

13347 82050 55659 280XX

21514 30017 43335 64596

82851 82433

EXAMPLE OF PLOTTED REPORT

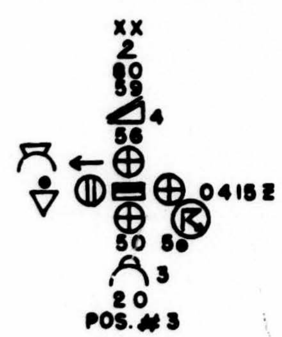


Fig. 5-6. Plotted report from reconnaissance aircraft.

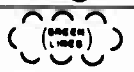
WEATHER DISTRIBUTION SYMBOLS	
	5 TO 8/8 HIGH CLOUDS (CI, CS, & CC)
	1 TO 4/8 HIGH CLOUDS (CI, CS, & CC)
	5 TO 8/8 MIDDLE CLOUDS (AS, & AC)
	1 TO 4/8 MIDDLE CLOUDS (AS & AC)
	7 TO 8/8 LOW CLOUDS (SC, ST, & NS)
	4 TO 6/8 LOW CLOUDS (SC, ST, & NS)
	1 TO 3/8 LOW CLOUDS (SC, ST, & NS)
	7 TO 8/8 LOW CLOUDS (CU)
	4 TO 6/8 LOW CLOUDS (CU)
	1 TO 3/8 LOW CLOUDS (CU)
	CUMULONIMBUS
	THUNDERSTORMS
	SHOWERS
	RAIN
(CLEAR)	CLEAR AREAS WILL BE LEFT BLANK

Table 5-1. Symbols used in a weather distribution map.

all the weather data in a reconnaissance observation are to be plotted, a chart with a scale no smaller than 1:5,000,000 may be considered practical. Larger scales are optional. For purposes of uniformity with charts used for wind analysis, a Mercator's projection is recommended.

Off-time reports should be indicated as such, especially if reconnaissance runs are used (see Section 4430). Any additional information, such as radar reports, sferics reports or clear language descriptions of weather or cloud phenomena should be entered at the appropriate place. It is very important to plot summaries of material obtained from air-crews during debriefings. All pertinent weather or cloud data from land or ship reports, pomars, metrars, etc., can be adapted to the plotting model shown in figure 5-5 and plotted on the weather distribution map.

A completed weather distribution map graphically represents the amount, location and extent of high, middle and low clouds and the type, location and extent of precipitation. The symbols used in constructing the weather distribution map are shown in table 5-1 on the opposite page. These symbols were designed to indicate the amount of cloud cover as well as the type of cloud reported. The darker, or more predominant symbols indicate a greater cloud coverage. If care is exercised in spacing the symbols, the areas of scattered clouds will appear to be light in color or tone, while the broken or overcast areas will appear darker and more congested.

Three types of colored pencils and assorted rubber stamps are used in constructing the map. Since the stamp pad ink has a slight tendency to smear when freshly applied, it is suggested that the clouds and weather be applied in the following order:

The middle clouds in orange and red shading.
The high clouds in dashed or continuous green lines.
The low clouds (rubber stamps, preferably).
Precipitation (rubber stamps, preferably).

If rubber stamps are not available, the individual symbols may be drawn in pencil or ink. This is an extremely tedious process, however, and is not recommended.

5400. ANALYSIS OF WEATHER DISTRIBUTION MAPS.

If weather distribution maps form a part of the standard daily analysis in the weather station, the task of drawing the map is greatly simplified by the fact that the major weather systems of the tropics have continuity from map to map. From day to day, large-scale systems, moving through the area of operation, may show the same characteristic intensity, as judged by the amount, depth and arrangement of the clouds and the precipitation patterns. On the other hand, they may increase in intensity or die away, but, except perhaps during the explosive deepening of some typhoons and hurricanes, the changes are sufficiently slow to be followed easily on the map sequences. In some regions, for example the Marshall Islands, systems may form aloft and remain stationary for many days, slowly increasing in intensity from day to day. Under these circumstances, the whole process of deterioration in the weather can be followed in detail and forecast by simple extrapolation.

In describing the method of analysis, we are assuming that this convenient continuity cannot be used. We will suppose that the forecaster is confronted with the problem of analyzing a weather distribution map without the benefit of previous knowledge. In practical affairs, this situation may arise when weather distribution analysis is not part of the station routine, but an operational emergency requires the immediate analysis of the weather by a man comparatively inexperienced in the meteorology of the area. Confronted with a map plotted in the manner already described in section 5300, how should he proceed?

First, if he has not already become familiar with the climatology of the area, he should consult the best available information on the cloud and weather characteristic of the season and place. If the equatorial trough lies near or across the area, he should be on the alert to discover, in the reports,

evidence of "equatorial fronts",- lines of cumulus-congestus or cumulonimbus that simulate the cold fronts of high latitudes. If he is working in a trade-wind area, he should be prepared, before starting the analysis, to find characteristic distributions and heights of cumulus and stratocumulus. In other words, his climatological knowledge should help him form a mental picture of the normal weather distribution map of the region. If he finds radical departures from this pattern, he will know that he must pay particular attention to the anomalous features, making every effort to delineate them properly on the map.

With this preparation, he should then examine the aircraft reports, first priority being given to any reconnaissance data. If, as is customary in some regions, transient air-crews have submitted pictorial cross-sections of the weather along the air-routes to the station, these should also be examined at this time. Particular attention should be given to plain-language descriptions of cloud lines, "fronts", cirrus bands, alto-systems and lines marking abrupt changes of cloud form, as these usually indicate the extent and orientation of major cloud systems. The analyst should outline these features lightly in lead pencil. If he has the opportunity of discussing his map with an air-crew that is being de-briefed in the station, he should never neglect to do so.

Next, with orange and red pencils, he should outline the areas of middle cloud according to the conventions already described. At first, all areas of middle cloud should be outlined by following the reports rather mechanically and making reasonable interpolations between reports. Then, the resulting picture should be examined with an eye to the reports of cumuliform clouds. If the cumuliform clouds over most of the region are small, cumulus-congestus and cumulonimbus being absent, any alto-cloud is probably independent. Some attempt should be made to distinguish an organized shape to the system. Independent systems will usually be band-like or sickle-shaped with frayed edges of patchy altocumulus. When the independent alto-systems have been shaped to the satisfaction of the analyst, he should then shade them according to the conventions.

All middle cloud will not be independent. If orographic cumulus or cumulonimbus is widespread, fairly large patches of middle cloud may be reported in their neighborhood. However, these patches will be detached from one another and will rarely form a very extensive alto-system with a definite shape. If reports of cumuliform cloud indicate that the middle cloud in any part of the region is dependent, the analyst should keep the area covered by his shaded drawing of the cloud to the minimum compatible with the reports and the topography; at the same time he should show clearly the connection between the middle cloud and the convective pillars. In passing, it should be emphasized that, over the open sea, lines of cumulus-congestus or cumulonimbus are often associated with alto-systems (see Section 5240), but this does not necessarily mean that the middle cloud is dependent; on the contrary, the most likely situation, during the late stages of deepening of an upper-level cyclone, is for one or more asymptotes of convergence, with accompanying cumulus or cumulonimbus lines, to develop under a pre-existing deep alto-system and to merge with it aloft.

The next step is to delineate the upper cloud in green, according to the conventions. Follow the same principles as were used in drawing the middle

cloud. Usually there is little difficulty in distinguishing between dependent and independent cirrus. Almost all independent alto-systems will be accompanied by cirrus or cirrostratus sheets, either separate and at a much higher level, or fused with it in the areas of precipitation. Usually the cirrus sheets will cover a wider area than the alto-system, and often cirrus in broad bands covers a great area on either side of the alto-system, the bands being oriented parallel to the main axis of the alto-system.

The delineation of cirrostratus sheets of independent formation can be of great assistance in tracing the genesis and development of an upper-level cyclonic system. At early stages in the development of such systems, very little middle cloud may be present, and the circulation may be evident only in the layers above 30,000 feet. On the weather distribution map, however, this early stage of development is often accompanied by extensive sheets of cirrostratus. A series of maps which clearly shows the development of the cirrostratus sheets is often the best way to follow the gradual intensification of the system.

By the time he has analyzed the distribution of the middle and high clouds, the forecaster should have studied most of the lower cloud reports and should have formed definite opinions about their distribution. Cumulus-congestus and cumulonimbus of orographic origin, for example, should be obvious by this time; they should be entered in their correct positions by means of the rubber stamps. The more definite front-like lines of cumulus and cumulonimbus, if any have been reported as such by aircraft, should be clearly indicated next. At the same time, other reports of cumulonimbus or very heavy cumulus, even if they are not orographic, should be examined. Do these clouds form part of a linear system that has not been identified as such by air-crews, or are they more or less evenly spread over a wide area? Remember that the linear orientation is frequent, but not the only possible arrangement. Often, very extensive areas may be covered by more or less uniform distributions of cumulonimbus. Delineate these areas as sharply as possible.

Next, take the reports of smaller cumulus and enter the proper symbols. These clouds will usually be found more or less evenly distributed over very large areas. Note any dependent stratocumulus reported, and extend the analysis to any areas of widespread independent stratocumulus that fall within the operational region. Enter all precipitation and special phenomena, such as thunder, lightning or hail (the latter usually not reaching the ground). The analysis should then be complete.

When the analyst has completed all of the procedures described above, he will find that he not only has an excellent chart that can be used for briefings but also has obtained an exceptionally thorough knowledge of the distribution and form of clouds and weather over the area in which he is interested.

In deciding between linear and areal distributions of clouds, one very important point must be kept in mind. Middle and upper clouds, and the upper portions of cumulonimbus clouds, can be seen at great distances by aircraft flying between 10,000 and 20,000 feet. They may be reported by either transient or reconnaissance aircraft long before they are encountered. Figure 5-7 illustrates the mistakes in analysis that may be made through neglect of this principle. The top portion of the diagram shows the reports from a reconnaissance aircraft. If the analyst forgets that observers on high-flying air-

5400.

craft can see such clouds from a great distance, the result may be the incorrect analysis shown in the middle of the figure. If he considers this fact, however, he should obtain the correct analysis, as shown in the bottom portion of the figure.

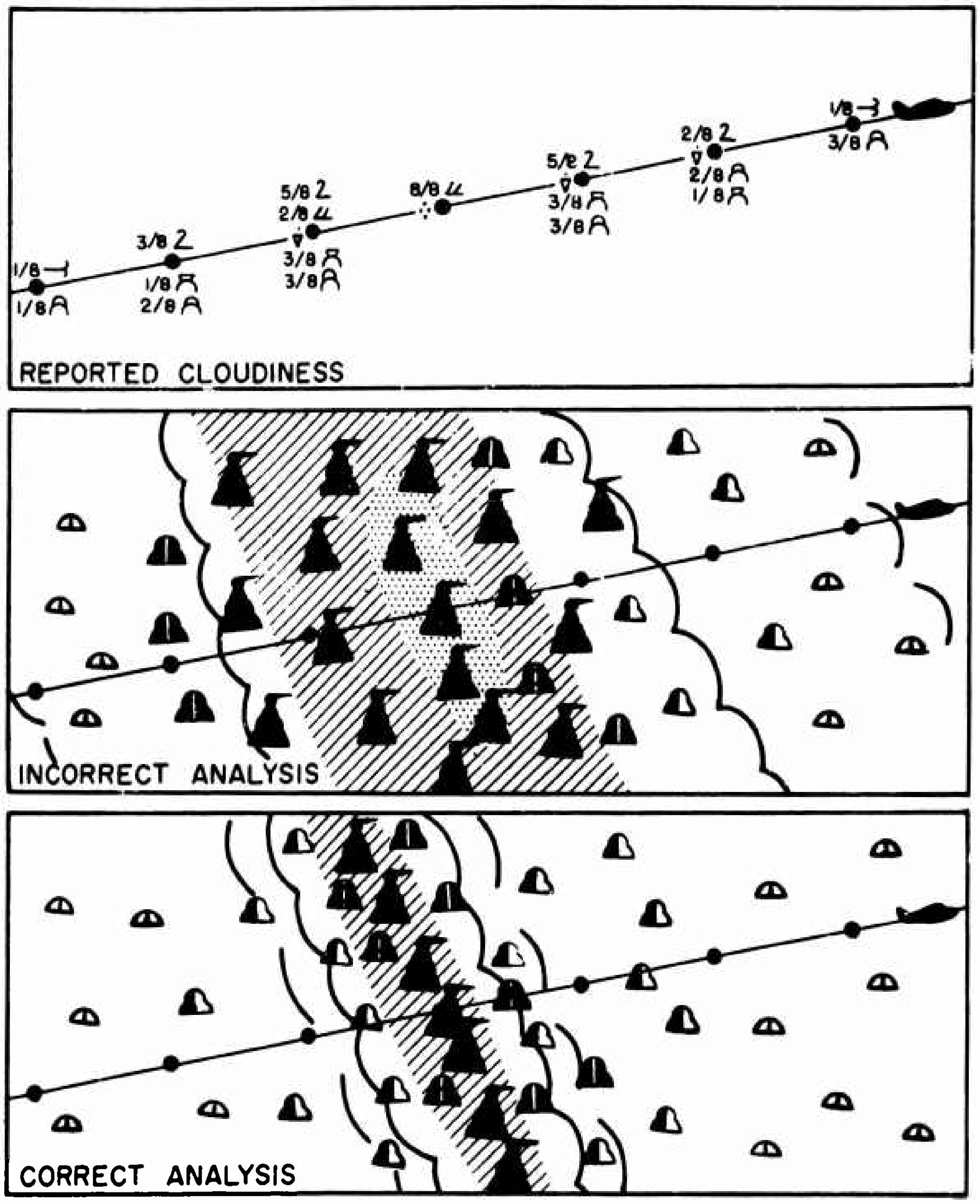


Fig. 5-7. Misinterpretation of cloud distribution from aircraft reports.

6000. THE CORRELATION OF WIND AND WEATHER

6100. THE PRINCIPLES OF CORRELATION.

The complete analysis of a synoptic situation is reached when the analyst has drawn wind maps for all levels in which he is interested, studied a series of time-sections which link the various levels in the vertical and in time, drawn a weather distribution map, and has a clear concept of the manner in which all of these graphs are correlated, one with another. This section deals with the various means by which this clarification may be attained.

All practical synoptic methods used in weather forecasting today are based upon two empirical discoveries, both made over a century ago. The first is that thick clouds and "bad" weather are associated with one type of atmospheric circulation (usually a cyclone); "good" weather is associated with a different type of circulation. The second is that the same circulation patterns, cyclonic, anticyclonic, troughs, etc., can be recognized from day to day on synoptic maps and that they travel from place to place, carrying their characteristic weather with them. All modern methods of forecasting are based on refinements of these two discoveries and upon a better understanding of the reasons for the correlations.

The development of thermodynamics during the last century very soon led to the realization that the vast majority of clouds formed as a result of vertical motion in the atmosphere. Upward motion of a stream or mass of air leads to adiabatic cooling, condensation and in some cases, precipitation; downward motion produces adiabatic warming, stability and evaporation of water and ice particles. Strictly speaking, then, the observed correlations of wind and weather depend upon the correlation of widespread upward motion with one type of horizontal circulation, and of widespread downward motion with another. The vertical motions are not observed; however, they can be derived, either quantitatively or qualitatively, from well-analyzed horizontal wind maps. This matter is discussed in section 6210. In principle, therefore, the weather distribution can be derived from a complete knowledge of the wind field. Given a set of wind maps for all levels in the troposphere, the tropical analyst, with sufficient time, should theoretically be able to infer what the weather distribution map should look like, even if he has not analyzed it. Actually, he does not have time to do this quantitatively in the weather station, nor, in general, are his observations sufficiently dense to give him the required accuracy (which must be great) in the wind analyses. So, in practice, he has to use the weather distribution maps to check his wind analyses and vice versa. This process is illustrated in section 6300; when properly carried out, the forecaster can obtain a complete view of the tropospheric wind regime over his area of operation, including a qualitative knowledge of the vertical motions. Then, and only then, is he in a position to attempt to forecast changes in this regime. A successful forecast of the wind field, including the vertical motions, should lead to a successful forecast of the weather distribution. The art of deriving prognostic wind maps from the analysis is, therefore, the prime goal of every tropical forecaster; it is the art of extrapolation, simple or complex. The skill of the forecaster depends upon his

knowledge of the appropriate type of extrapolation to use in a given situation. Since the field of the vertical component of vorticity plays an important role in formulating the prognosis, it is briefly discussed in section 6220 and 6400.

6200. SECONDARY FIELDS DERIVED FROM THE WIND MAP.

From a pressure map, a forecaster in high latitudes can derive another, secondary map, the map of the pressure gradient. Theoretically, he could compute, from such an analysis, a complete wind speed analysis. In practice, this is never done; the gradient or geostrophic wind scale is used directly on the isobaric map, then the wind speeds are read only where required. Nevertheless, when the forecaster uses his scale, he is dealing with a secondary, derived field. The analogy in wind field analysis is more complicated since, in this case, he starts with a vector field rather than a scalar field. Note that, in the isobaric case, he carries out a process of differentiation, that is, he finds the rate of change of the pressure in a specified direction. The two secondary fields derived from the wind field are likewise obtained by differentiation, by finding the rates of change of wind speed and direction in certain specified directions. These secondary fields are the field of horizontal velocity divergence and the field of the vertical component of vorticity. Consider the point P on a wind diagram, as in figure 6-1; at this point there is a definite wind speed and direction obtainable by measurement

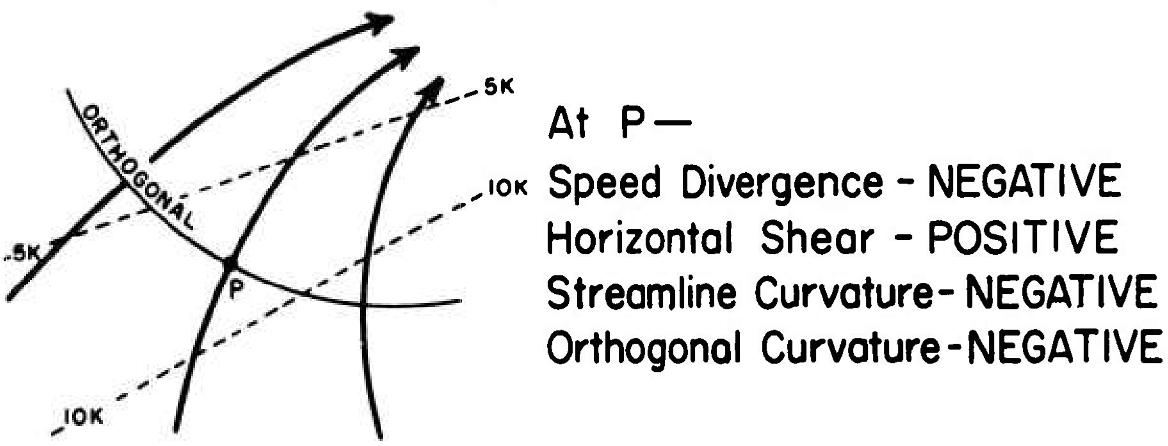


Fig. 6-1. Derivations of the wind field.

on the wind map. In addition, the wind speed is changing spatially at a definite rate at the point, and so is the wind direction. At P, we can measure the spatial change (whether of wind speed or direction) in two convenient directions; (1) along the streamline through P and (2) at right angles to the streamline through P. Four measurements, in addition to the wind speed and direction at the point, can be made at P; they are:

The rate of change of the wind speed along the streamline, called the speed divergence. If the speed is increasing downstream, this term is positive, if decreasing, negative.

The rate of change of the wind speed at right angles to the streamline, called the horizontal wind shear. If the wind speed

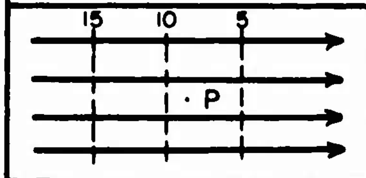
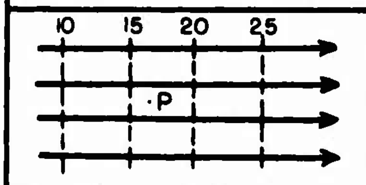
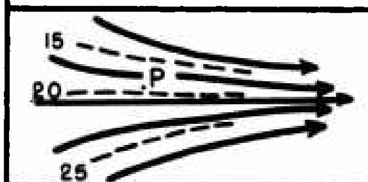
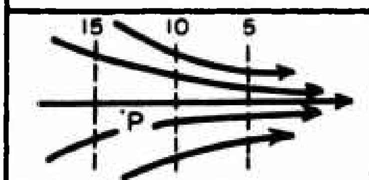
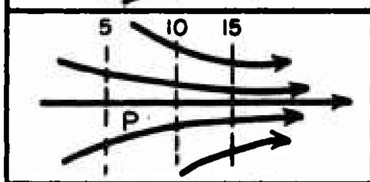
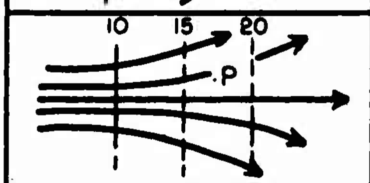
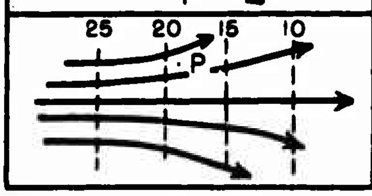
PATTERN	SIGN AT P OF ——		
	SPEED DIVERGENCE	ORTHOGONAL CURVATURE TIMES WIND SPEED	TOTAL DIVERGENCE
	−	0	−
	+	0	+
	0	−	−
	0	+	+
	−	−	−
	+	−	INDETERMINATE EXCEPT BY EVALUATING EACH TERM
	+	+	+
	−	+	INDETERMINATE EXCEPT BY EVALUATING EACH TERM

Table 6-1. Divergence Combinations.

is higher on the right of the streamline, looking downstream, this term is positive, if lower, it is negative.

The rate of change of wind direction along the streamline, called the streamline curvature. If the direction changes counter-clockwise downstream, this term is positive; if it changes clockwise, it is negative.

The rate of change of wind direction normal to the streamline, called the orthogonal curvature. An orthogonal is a line drawn at right angles to all of the streamlines which it intersects. If the neighboring wind directions diverge away from the streamline through P, this term is positive. If they converge, it is negative.

Clearly, measurements of these four quantities could be combined with one another in many different ways. Because they are both theoretically and practically the most important, only two combinations of the quantities, called respectively the horizontal velocity divergence and the vertical component of vorticity, need be considered by the analyst. Since no ambiguity can arise in this text, these quantities will be abbreviated to the divergence and the vorticity, respectively.

6210. The Divergence.

We define the divergence as follows:

Horizontal velocity divergence equals the speed divergence plus the streamline divergence; the streamline divergence being the product of the orthogonal curvature and the wind speed.

If we were to draw a very small circle around the point P on the wind map, figure 6-1, this quantity would measure the rate at which air was flowing horizontally across the boundary of the little area around P; hence the term divergence. Negative divergence is often called convergence by the synoptic meteorologist. Note that the smaller the wind speed is at the point P, the less is the magnitude of the streamline convergence. This illustrates the fallacy of the common practice of synopticians of judging the magnitude of the divergence solely by the angle between the streamlines (orthogonal curvature). This can be misleading in respect not only of magnitude but also of sign. The speed divergence is often larger than the streamline divergence and may be of opposite sign, so that a portion of the wind field, judged to be convergent on the basis of the streamlines alone, may actually be divergent. Table 6-1, on the previous page, illustrates possible combinations.

If the divergence is measured at many points on the wind map and the resulting distribution plotted on a separate map, a scalar analysis of the divergence can be made. There is rarely time for this in the weather station. However, spot measurements can easily be made on the wind map, and large positive and negative areas can often be discovered simply by inspection. To compute the divergence quickly at selected points, the only apparatus needed is a transparent plastic curvature scale ruled with a set of concentric arcs. The arcs should be labeled, each with a number obtained by dividing the radius

of the arc, in degrees of latitude, in terms of the scale of the map being used, into 1. Proceed as follows:

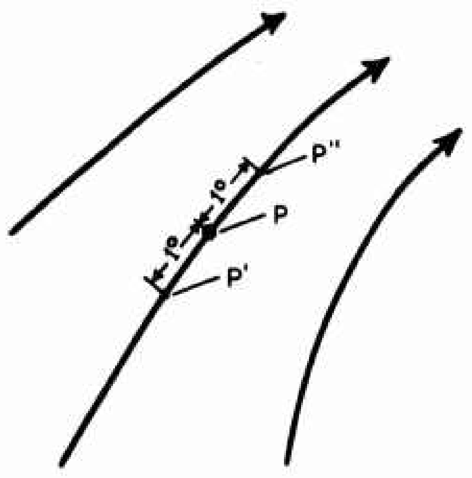


Fig. 6-2. Technique for measuring Horizontal speed divergence.

(1) Measure along the streamline through the point P a distance of 1° latitude upstream and 1° latitude downstream, as in figure 6-2. Mark the points P' and P", respectively.

(2) Algebraically subtract the wind speed (knots) at P' from that at P" and divide the difference by 2 to obtain the speed divergence. Remember the sign convention.

(3) At P, carefully fit an arc on the curvature scale so that it cuts the streamline that goes through P, as well as the streamlines on either side, at right angles. Read off the value on that arc. Remember the sign convention.

(4) Multiply this value by the wind speed at P. This gives the streamline divergence.

(5) Add the result of (2) to that of (4), having regard for the signs of the quantities. The result is the divergence in "practical units", actually in terms of "per 60 hours".

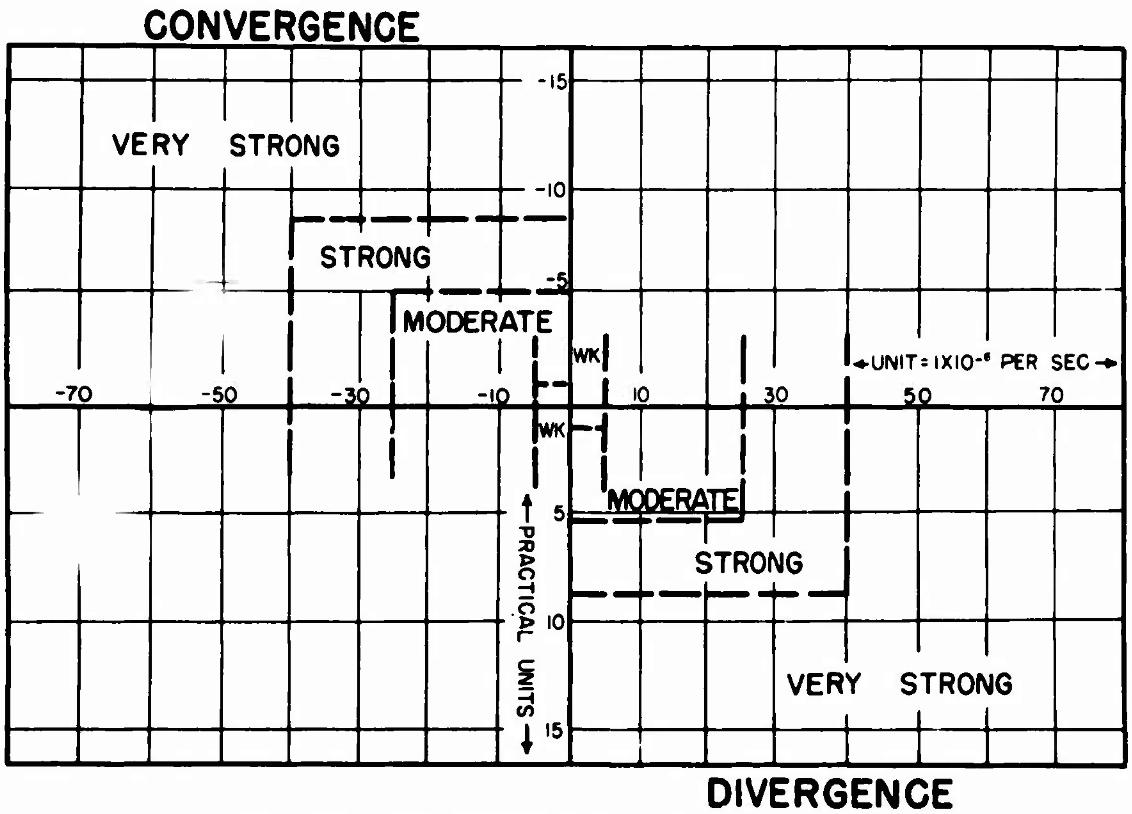


Fig. 6-3. Divergence conversion chart.

In theoretical work, the divergence is usually expressed in terms of "per second". Such units are unwieldy for the practical forecaster, who is

primarily interested only in the sign and the relative strength of the divergence. Figure 6-3 shows the divergence in terms of the practical units and, for those who desire to make comparisons or compute vertical motions, in terms of "per second". It also shows the qualitative application of the terms "weak", "moderate", "strong", and "very strong" divergence in tropical meteorology. The forecaster is warned that these qualitative terms, weak, etc., may not be applicable to the same quantitative values of the divergence in higher latitudes.

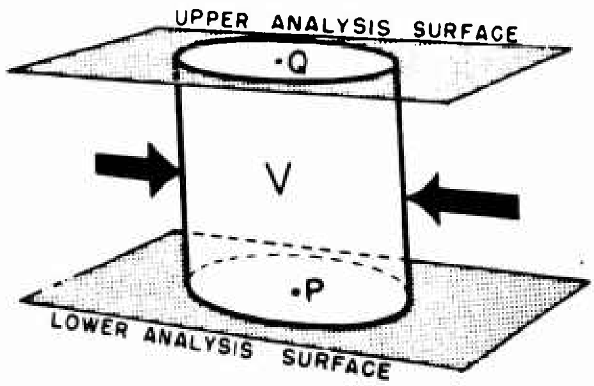


Fig. 6-4. Example of convergence into a cylinder.

The synoptic significance of the divergence is greatest in the lower layers. As already mentioned, it gives a measure of the rate of horizontal inflow or outflow across a small boundary drawn around the point of reference. If we now choose two maps, one above the other and very close together, and draw the same circle around the point P on the lower map and around the point Q vertically above it on the upper map, we may consider a small cylinder with vertical sides cutting the wind maps at these circles. The mean divergence of this cylinder will be one-half the sum of the divergences at P and Q. Suppose this mean is negative, i.e., there is, in the mean, convergence into the tiny volume V, as shown in figure 6-4. Then it is clear that either the density must increase inside V, or air must flow out through the circles at P and Q, or both these processes must occur. The great advantage of using divergence in the tropics is that, in these regions, density changes are known to be very small and to take place slowly. Therefore, from the synopticians viewpoint, convergence into the cylinder V means outflow through the circles at P or Q, or both. If the little cylinder is chosen so that its base rests on the level sea surface or on flat ground, there cannot be outflow at P but only at Q. In such a case, convergence into V means upward motion through the circle at Q; divergence out of V would mean downward motion through the circle at Q.

If we wished to make a computation of vertical motion at some fairly high level, we would have to start with a little cylinder resting on the ground, compute the vertical motion through its upper surface, then compute again for a similar cylinder placed on top of the first, and so on up to the desired level. An illustration of this technique is given on the next page in figure 6-5. Notice that, in the case of the upper cylinders, it is the net outflow or inflow (the difference in vertical motion at the top and bottom) that is derivable from the divergence. This fact sometimes helps the forecaster to make an estimate of the sign of the vertical motion from a single map at high levels. As a general rule, in the upper tropical troposphere, downward motions are widespread but of small magnitude; upward motions are more restricted in area but are comparatively large. If a restricted region of strong convergence is found on an upper tropospheric map, therefore, we know that the net motion in the vicinity is upwards, since strong downward motions are unlikely. The converse inference cannot be made; we cannot infer from the existence of

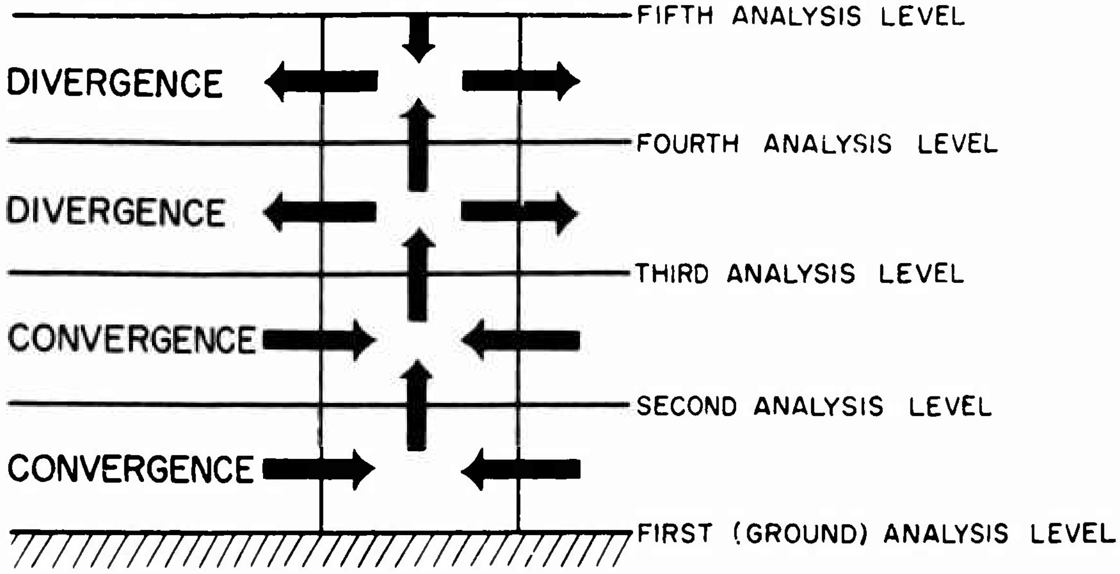


Fig. 6-5. The cylinder technique for computing vertical motions.

strong divergence that there will be downward motion near the analysis level. Note, for example, the distribution of flow through the cylinder between analysis levels 3 and 4 in figure 6-5.

In practice, the divergence at a point on the 1,500 or 2,000 foot wind map is a reasonable approximation to the mean inflow or outflow across the walls of a narrow cylinder with its base on the ground and its top at 3,000 feet. In general, a qualitative estimate of these motions correlates excellently with the weather distribution chart. Some examples are given in section 6300.

6220. The Field of Vorticity.

Vorticity in a fluid or a gas, such as the atmosphere, is similar to the rotation of a solid body. We define the vertical component of the vorticity as follows:

> *The vertical component of vorticity equals the wind shear plus the product of the streamline curvature and the wind speed.*

The procedure for computing the vorticity is as follows:

(1) Draw a line (either real or imaginary) through the point P and at right angles (normal) to the streamline that passes through P. (Until the analyst becomes accustomed to interpolating streamlines by eye, it may be necessary for him actually to draw a streamline that will pass through that point.) Along this line, to the left looking downstream, measure a distance of 1° of latitude from the point P and label that point P'. Similarly, measure 1° of latitude to the right

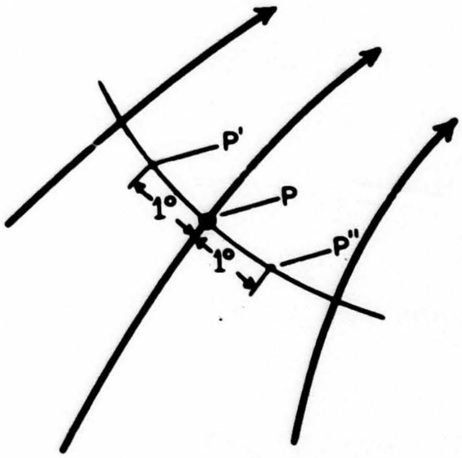


Fig. 6-6. Technique for measuring horizontal wind shear.

and label that point P" (Fig. 6-6).

(2) Algebraically subtract the wind speed (in knots) at P' from that at P" and divide the difference by 2 to obtain the horizontal wind shear. Remember the sign convention.

(3) Carefully fit an arc of the transparent curvature scale over the streamline that passes through P so that the arc and the streamline have the same curvature. Read off the value on that arc. Remember the sign convention.

(4) Multiply the arc value, obtained from (3) above, by the wind speed at the point P.

(5) Add the results of (2) and (4), above, having regard for the signs of the quantities. The result is the vorticity in the same "practical units" described in section 6210.

These computations are most important in prognosis and continuity, rather than analysis. Therefore, they are discussed in section 6400.

6300. CORRELATION OF WIND AND WEATHER DISTRIBUTION MAPS.

The following examples are chosen from analyses of the weather in the Marshall Islands. Each example illustrates analytic principles applicable to that region. The principles are not to be taken as generally valid throughout the tropics, although some of them may well be of wide application. They are described here to show the type of generalization that can be developed by experience in the correlation of wind and weather maps. The forecaster, for his own benefit within his area of operation, should constantly seek to develop such analytic principles and should record those that he finds reliable in his notebook.

6310. Example One: Northern Marshall Islands; 0000, G.C.T., 14 February 1954.

First Analytic Principle. In regions of moderate to strong divergence at 2,000 feet, the predominant cloud is usually cumulus humilis with less than 4/8ths coverage.

Discussion. The application of this principle is illustrated by region A on figure 6-7. The aircraft reports indicate small amounts of cumulus about 1,000 feet thick and the streamline map for 2,000 feet (Fig. 6-8) shows the presence of an asymptote of divergence in this vicinity. The wind speeds have weak gradients and the total divergence is moderate; in the vertical the wind direction does not alter much over the first 10,000 feet (see Fig. 6-9) but the speed decreases from 25 knots at 2,000 feet to about 5 knots 10,000 feet. However, examination of time-sections for Rongerik, Wake and Eniwetok (or analysis at intermediate levels) shows that this shear is not evenly distributed with height; the wind speeds remain approximately 20 knots in region A up to 7,000 feet, then rapidly decrease to about 5 knots. This point is

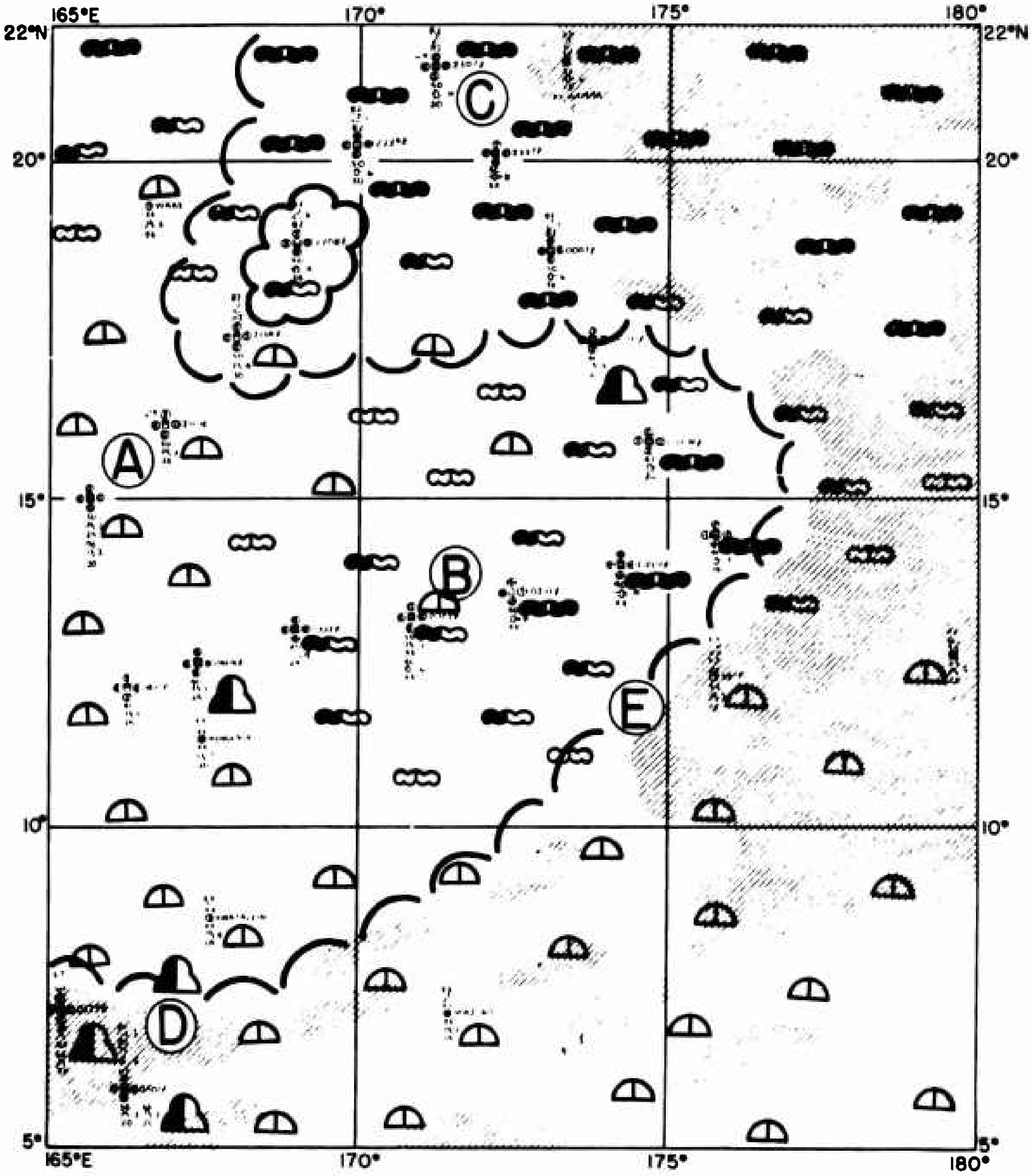


Fig. 6-7. Weather distribution analysis, Marshall Islands area, 0000 G.C.T., 14 February 1954.

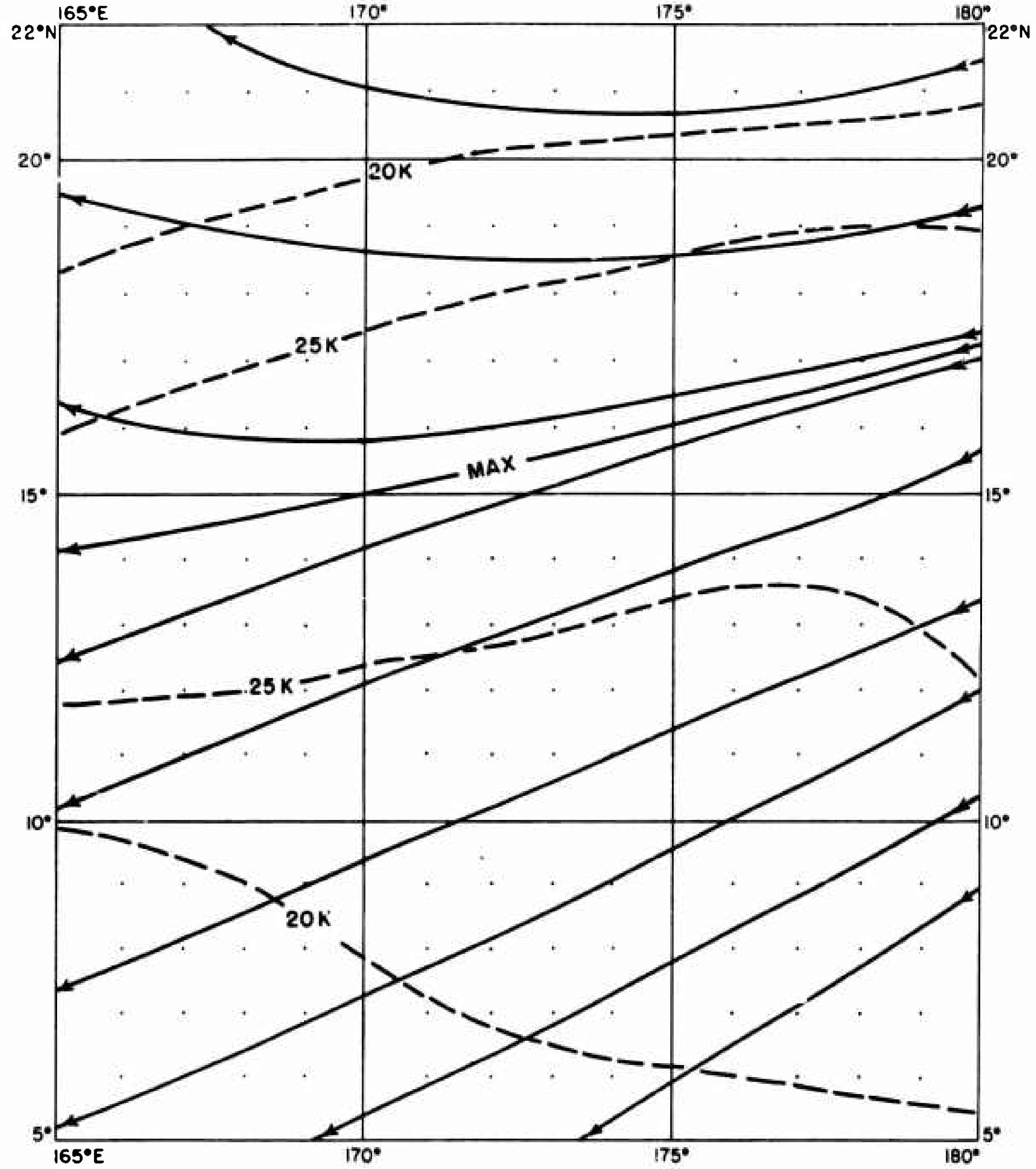


Fig. 6-8. 2,000 foot streamline-isotach analysis, Marshall Islands area, 0000 G.C.T., 14 February 1954.

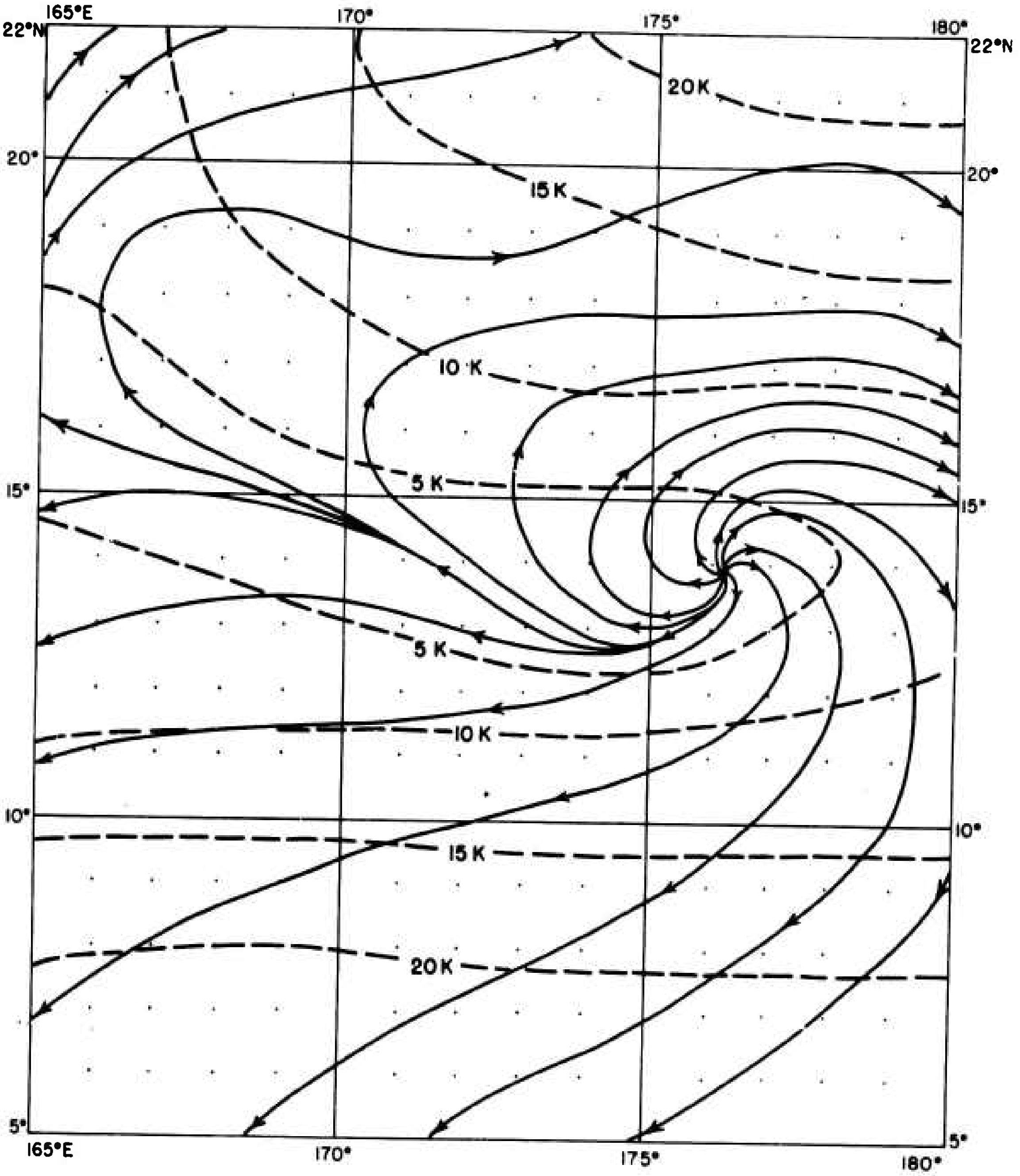


Fig. 6-9. 10,000 foot streamline-isotach analysis, Marshall Islands area, 0000 G.C.T., 14 February 1954.

6310.

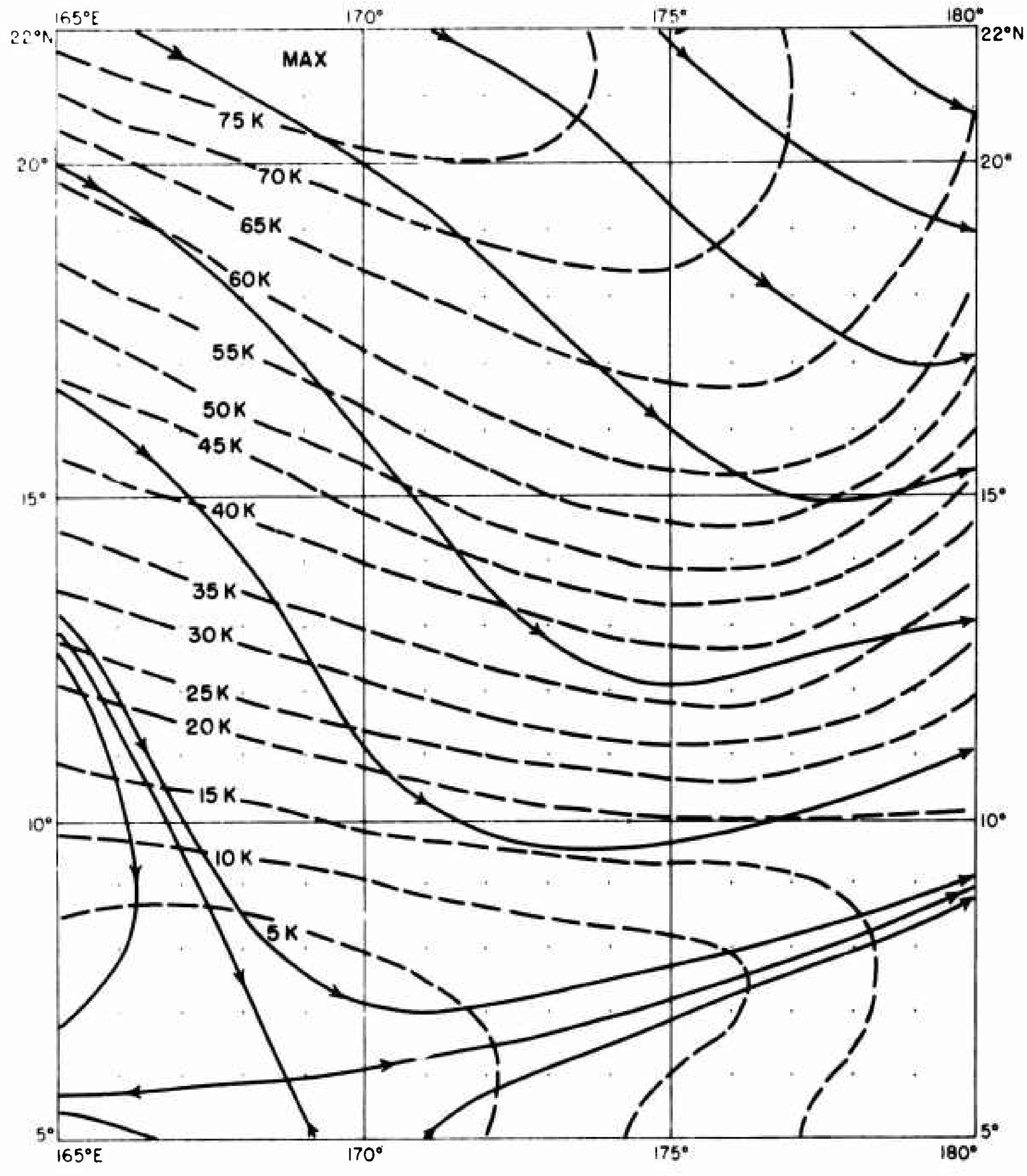


Fig 6-10. 30,000 foot streamline-isotach analysis, Marshall Islands area, 0000 G.C.T., 14 February 1954.

important in the application of the next principle. Note that small amounts of cumulus occasionally break through to the 7,000 foot level (see the aircraft report on the 15th parallel Fig. 6-7).

Second Analytic Principle. When great vertical shear accompanies moderate divergence, the cumulus humilis (or cumulus mediocris) will be drawn out and sheared off. The cumulus will be accompanied by 4/8th or more of dependent stratocumulus, and the amount of cloud as seen from an aircraft will increase, owing to the lean of the cumuli.

Discussion. This is illustrated by the weather distribution in region B of figure 6-7. Here as figures 6-8 and 6-9 show, the wind not only changes speed between 2,000 feet and 10,000 feet but there is a marked change in direction associated with the presence of an anticyclone at 10,000 feet. Note the variation in interpretation of the sky made by the weather observer in the aircraft; he classifies the sky first as containing 8/8ths of stratocumulus and cumulus and finally 5/8ths of stratus. Amounts of cloud reported are greater than in region A, though the divergence probably is not much less at 2,000 feet in region B. On the weather distribution map (Fig. 6-7) the varying reports of sky cover in region B are interpreted in the same way, namely as broken stratocumulus blown from the tops of cumuli.

Third Analytic Principle. North of the trade wind maximum, in the Northern Hemisphere, the vertical shear in the wind in the lower layers is usually very great and the trade wind inversion low. The predominant cloud is, in the great majority of cases, stratocumulus. The clouds will exist in broken patches if the 2,000 foot wind pattern is divergent; even with weak to moderate convergence at this level, very little cumulus forms - the result is usually an increase in the amount of stratocumulus, up to 8/8ths sometimes being encountered west and south of the subtropical anticyclonic centers.

Discussion. In region C, large amounts of stratocumulus, approximately 2,000 feet thick, are reported by both the aircraft and the ship (Fig. 6-7). There is very weak, if any, convergence at 2,000 feet; at 10,000 feet there is marked divergence and the vertical shear between 2,000 and 10,000 feet is extreme.

Fourth Analytic Principle. When there is little vertical shear in the lower layers and the 2,000 foot map shows weak to moderate convergence south of the trade wind maximum, expect deeper cumulus; the cloud amount will also increase over that expected in divergent flow, but not to a very marked extent. Even with very strong convergence the cumuliform cloud will show many breaks, the general effect of increased convergence being to increase the depth of the convective cloud.

Discussion. In region D of figure 6-7, there is very little shear, the wind at 10,000 feet having almost the same direction and speed as that at 2,000 feet. There is weak convergence at 2,000 feet, very weak divergence at 10,000 feet. Cumulus up to 15,000 feet are reported. No showers have been reported in this area, but much further downstream (beyond the map limit), where the convergence at lower levels increases, widespread showers occur. It is probable that very light cumulus showers occur in region D but are not reported.

Fifth Analytic Principle. There is a marked tendency for small amounts (2-4/8ths) of both altocumulus, or altocumulus - altostratus, and cirriform clouds to lie just east of the axis of a weak trough in the upper westerlies provided the latter is a moving, high-latitude trough, not a stationary, major trough associated with a developing upper level cyclone.

Discussion. South of 15° N., particularly in region E, figure 6-7, the edge of the area within which small amounts of middle and upper cloud are reported runs very close to the axis of a weak, high-latitude trough which at this time is moving toward the Hawaiian Islands. The structure of the trough at 30,000 feet is shown on figure 6-10.

Sixth Analytic Principle. The jet stream sometimes extends into relatively low latitudes by "meandering" southward near the axis of a high latitude trough at 30,000 and 40,000 feet. When this occurs, the region of strong lateral shear on the south side of the west-wind maximum is often marked by small amounts of altocumulus and cirrus. So far as is yet known, middle and high overcasts are not formed in such regions.

Discussion. The broken middle and upper clouds associated with the weak trough at 30,000 feet extend westward from the trough axis north of 17°N. The 30,000 foot analysis (Fig. 6-10) shows the edge of a strong westerly jet to the north. The wind speed is particularly strong for the tropics between regions A and C. Note that this "jet cloud" consists mainly of cirrus.

General Remarks on the Situation: The synoptic picture in this area on 14 February 1954 is one of the simplest that one is likely to encounter in low latitudes. A high latitude meteorologist would probably classify it broadly as trade wind weather. The example emphasizes the fact that there are marked variations in clouds from place to place in the trade wind zone, variations that can be understood by considering not only the stability and vertical motion but also the vertical shear in the trade winds and the synoptic situation above 20,000 feet.

6320. Example Two: Marshall Islands at 0000, G.C.T., 6 April 1954.

Seventh Analytic Principle. An asymptote of convergence in the low-level streamline field will, if it coincides with a relative minimum in the speed field, be accompanied by a line of large cumulus-congestus or cumulonimbus. The system will resemble a cold front of high latitudes insofar as the weather and wind changes in its neighborhood are concerned, but in oceanic regions at least, no significant air mass differences across the boundary can be detected.

Discussion. The weather distribution map (Fig. 6-11) shows a well-marked line of cumulonimbus lying across the southern Marshall Islands. Its position and structure are fixed by the weather reports from the reconnaissance aircraft with as much precision as can be expected in oceanic regions. Note that its presence is revealed by three aircraft, working independently. The streamlines at 1,500 feet (Fig. 6-12) show that the cloud line coincides with an asymptote of convergence and that the isotachs run in such a way as to reinforce the convergence in the streamlines. The convergence of the speed field reaches relatively large values at 5° N., 170° E., and there are many

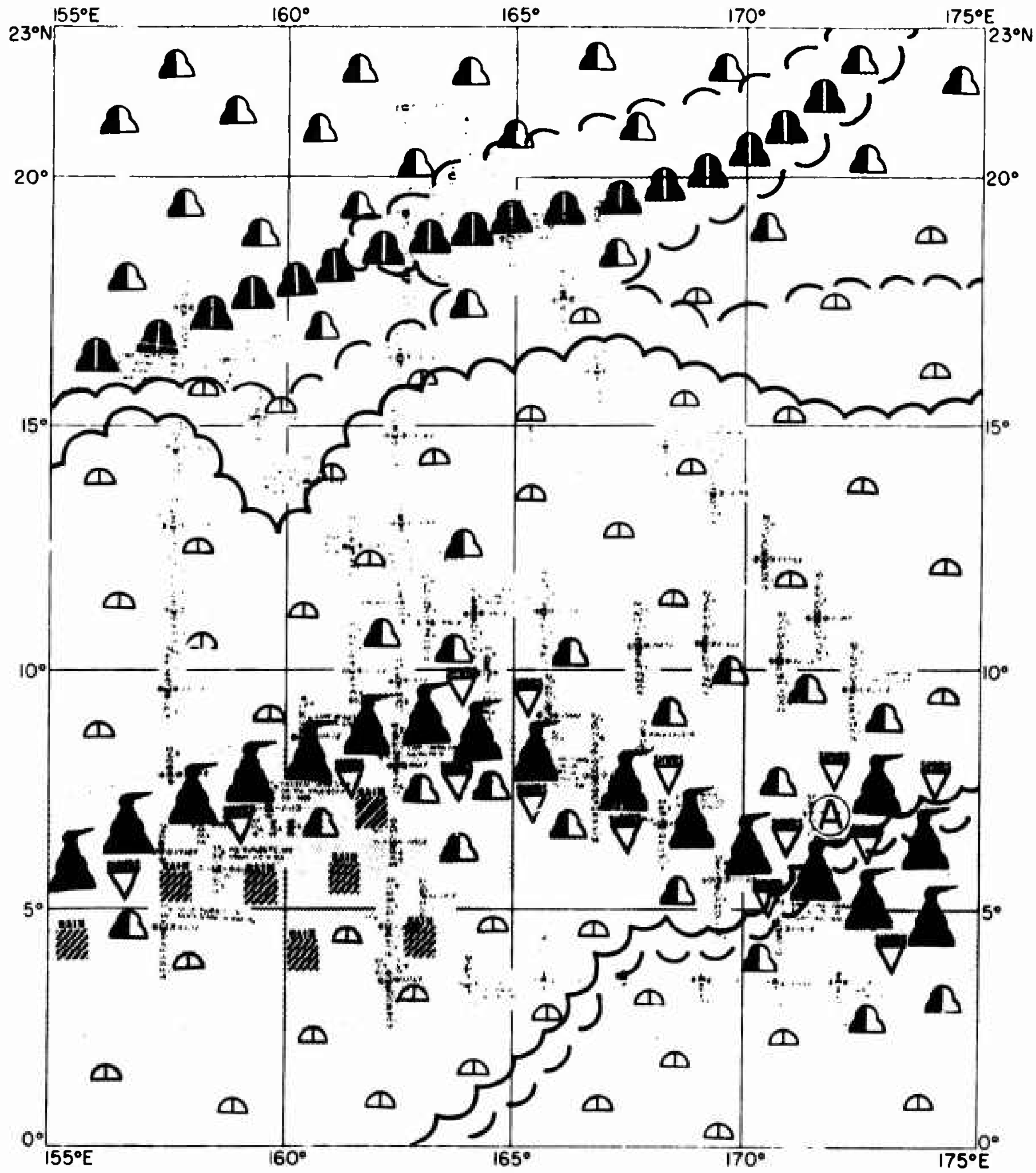


Fig. 6-11. Weather distribution analysis, Marshall Islands area, 0000 G.C.T., 6 April 1954.

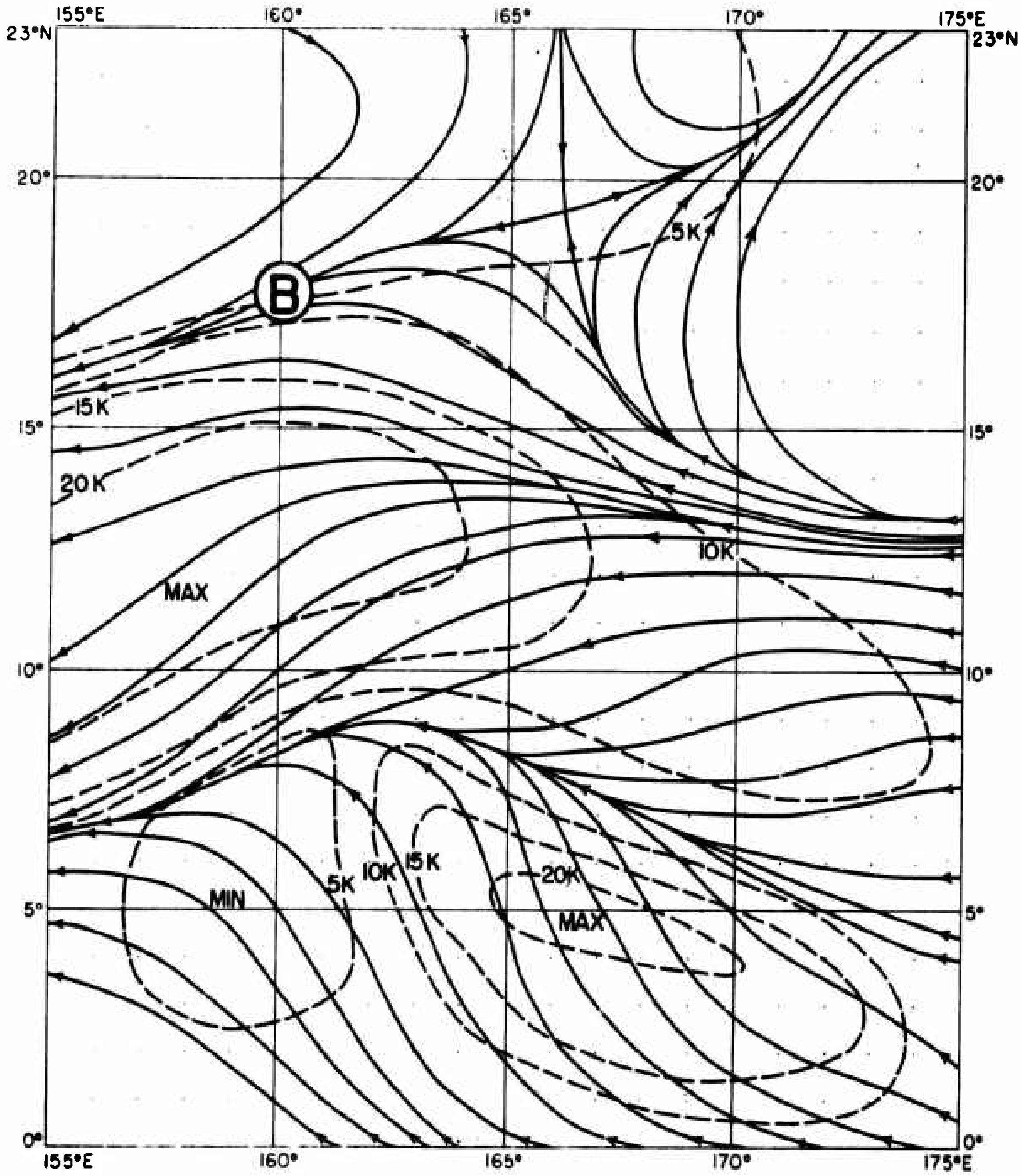


Fig. 6-12. 1500 foot streamline-isotach analysis, Marshall Islands area, 0000 G.C.T., 6 April 1954.

KWAJALEIN M.I. 6 APRIL 1954 0300 Z			KUSAIE M.I 6 APRIL 1954 0300 Z		
MB	HEIGHT	TEMP	MB	HEIGHT	TEMP
1008		28.2	1005		27.5
1000	240	27.5	1000	160	27.2
			954		23.5
850	4920	19.2	850	4830	21.2
			820		20.5
			793		17.2
700	10320	9.8	700	10250	10.5
612		4.5			
526		-3.5	541		-2.5
500	19270	-4.2	500	19180	-6.2
400	24930	-14.8	400	24800	-15.6
300	31850	-30.2	300	31700	-30.8
260		-38.5	268		-36.8
200	40850	-52.5	200	40710	-52.5
150	46770	-64.8	150	46630	-65.0
			141		-67.0
100	54660	-76.0			
87		-80.0			
62		-65.0			
50	68110	-63.2			

Table 6-2, (Left) upper air soundings for Kwajalein and Kusaie, 6 April 1954.

WAKE 5 APRIL 1954 2100 Z			WAKE 6 APRIL 1954 2100 Z		
MB	HEIGHT	TEMP	MB	HEIGHT	TEMP
1011		24.8	1013		26.5
1000	330	23.8	1000	390	25.2
850	4930	15.2	850	5000	15.2
839		14.5	819		13.5
816		10.8			
801		9.2	708		7.5
700	10220	5.2	700	10340	7.2
638		-0.2			
573		-3.5	595		0.2
556		-5.2	580		0.2
500	19010	-9.2	500	19180	-8.8
476		-11.2	459		-13.8
427		-16.2			
400	24570	-19.2	400		-17.5
363		-23.2			
300	31700	-36.8	300	31570	-33.2
			296		-33.5
			269		-39.2
200	40190	-56.0	200	40540	-52.2
150	46030	-67.5	150	46440	-66.0
			125		-71.8
			105		-74.0
100	53830	-78.0	100	54300	-70.0
94		-80.0	75		-79.0
			64		-72.0
			55		-69.0
50	67140	-66.0	50		-63.8

Table 6-3, (Right) upper air soundings for Wake, 5-6 April 1954.

showers outside the "frontal" area near A. In the frontal system of tropical forecasting, the cloud line in the southern Marshalls would be described as a typical "equatorial front" or "intertropical front". The soundings at Kwajalein and Kusaie at 0300 G.C.T., which would be, on any frontal interpretation, in the Northern Hemisphere and Southern Hemisphere air masses, respectively, have been tabulated in Table 6-2. The temperature differences between the soundings are the maximum to be anticipated in this type of situation in oceanic areas. At most they amount to 3° C.

Eighth Analytic Principle. Old polar fronts sometimes penetrate into the tropics. They rarely reach 15° N. or S. in oceanic regions. Such a remnant is often detectable as a line of towering cumulus, and this line between the old air masses also marks a change in cloud forms. The old front may, in these cases, appear on the lowest streamline map as an asymptote of convergence running E-W or NE-SW from the neutral point between two middle latitude anticyclones. In most cases, the temperature differences between the old air masses are negligible, even though the cloud line may persist for some time after the air mass contrasts have disappeared from the soundings.

Discussion. Conventional, surface-pressure analysis shows that the asymptote of streamline convergence marked B on figure 6-12 is continuous with a cold front that runs from the neutral point at Wake to a frontal wave centered at 38° N., 178° E. The weather distribution map derived from the reconnaissance reports clearly shows the corresponding clouds (Fig. 6-11). Two aircraft report its position independently and an excellent description of its structure is given by one of them. Note that the tops of the cumuli reach to 25,000 feet, which is barely high enough to produce cumulonimbi in these latitudes; in fact, no cumulonimbi are reported in the area. Passage of the line at Wake produced only a few showers. The extent of the air mass changes associated with the "frontal passage" may be judged from Table 6-3 on which are shown the soundings for Wake at 2100 G.C.T., 5 April, when the "front" lay north of Wake and at 2100 G.C.T., 6 April, when, as the wind shifts show, it lay south of the station. It will be noted that temperatures actually rose slightly over a considerable depth of the atmosphere, after the "polar air" moved in, - a not uncommon effect.

General Remarks on the Situation: The analyst is likely to find the "equatorial front" well developed in situations like this. An equatorial wave is passing over the southern Marshalls from east to west. At the same time a trough in the westerlies, associated with a frontal system, is moving from west to east in middle and high latitudes. The combination of these two systems gives rise to the rather unusual configuration of the trade wind zone over the northern Marshalls. Note the strong asymptote of divergence in that area (Fig. 6-12), a feature that is often present in this type of situation and which serves to separate the high and low latitude perturbations during their independent movement in opposite directions. Note also that heavy cloud and precipitation are found not only behind but also ahead of the positive axis of the equatorial wave, a feature in which this system differs from the "easterly wave" of the Caribbean.

6330. Example Three. The Marshall & Caroline Islands at 0000 G.C.T., 13 April 1954.

Ninth Analytic Principle. An asymptote of convergence in the lower streamline field is not necessarily accompanied by a cloud line. The speed distribution

in the neighborhood of the asymptote must always be closely examined and analyzed in as much detail as the observations permit. If strong speed divergence occurs along part of the line, there may be very little heavy cloud or precipitation accompanying it; further, bad weather may be found at some distance from the line, where speed convergence predominates.

Discussion. Figure 6-14 shows the 1500 foot streamlines and isotachs at approximately 0000 G.C.T., 13 April 1954. At first sight, the analyst might suppose that the asymptote of streamline convergence that lies across the southern Marshalls is entirely similar to that discussed in the previous

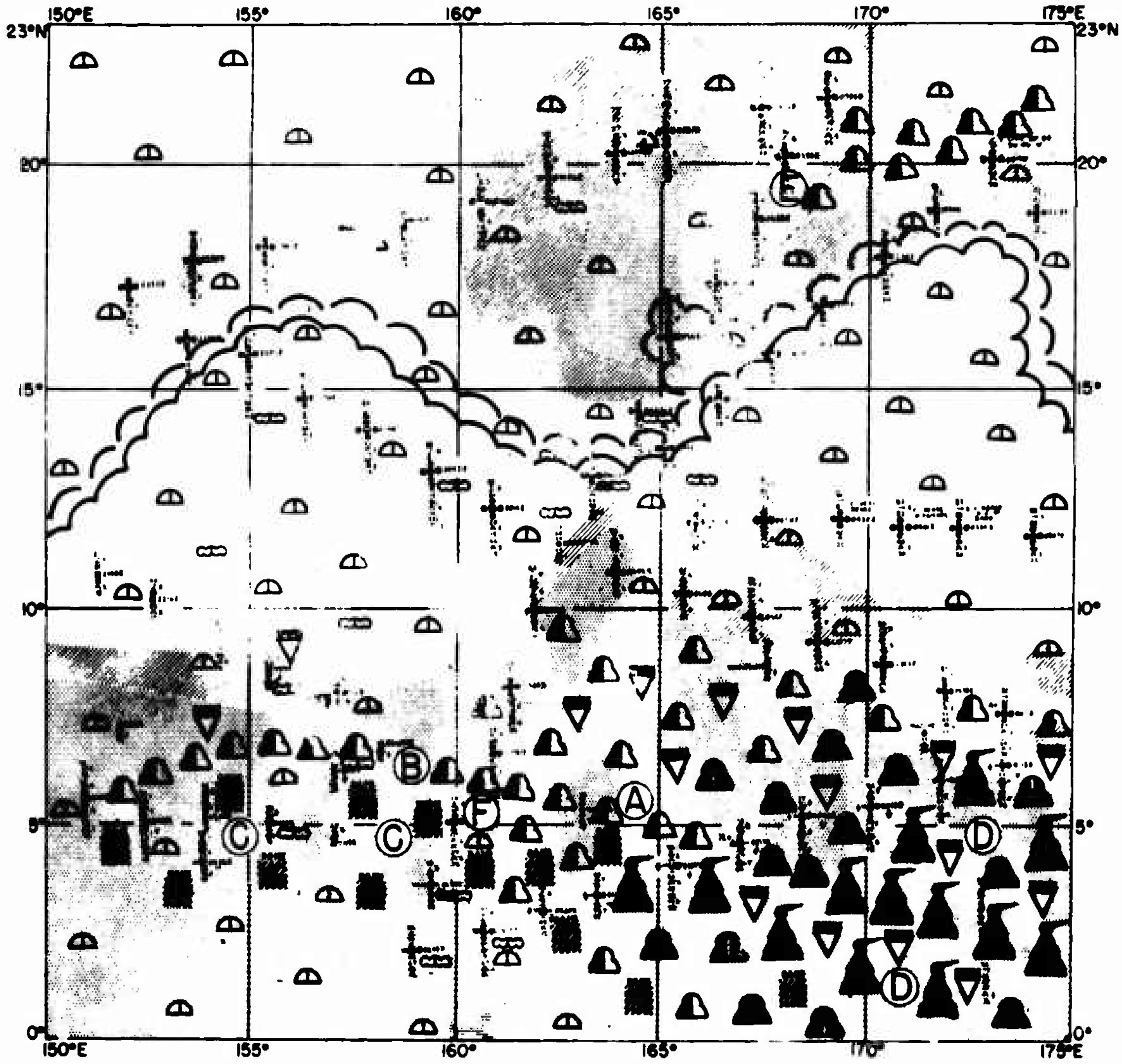


Fig. 6-13. Weather distribution analysis, Marshall Islands area, 0000 G.C.T., 13 April 1954.

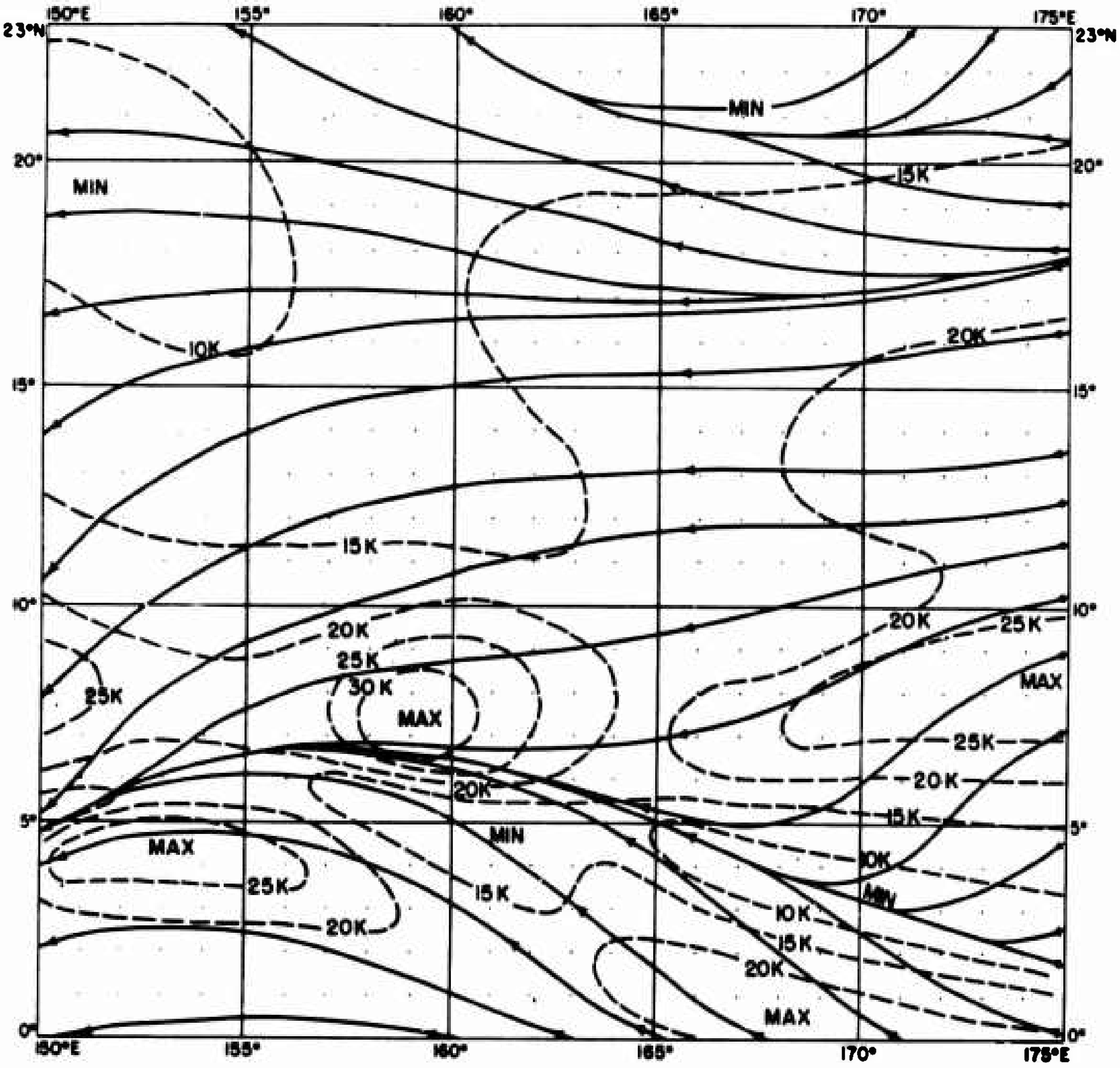


Fig. 6-14. 1500 foot streamline-isotach analysis, Marshall Islands area 0000 G.C.T., 13 April 1954.

example and displayed on figure 6-12. Under the frontal system of tropical analysis, indeed, both structures would be regarded as ,ical "intertropical fronts". Closer inspection of the figures reveals, however, that the distribution of the isotachs along and near the convergent asymptotes is very different in the two cases. From the east, up to point A on figure 6-13 it is true, the speed field reinforces the convergence of the streamlines, but from A to B there is strong speed divergence; there are sufficient reports to show that the speed maximum at B overlaps the asymptote, and that the speed minimum lies some distance south of the line. Turning now to the weather distribution map analyzed on figure 6-13, we see that cumulonimbi run from the east-southeast up to A, and beyond this point no definite cumulus line can be drawn, at least up to B. In the regions east-southeast of A such as those points labeled D, cumulonimbus is widespread. This can be correlated with the widespread strong convergence in the lower streamline and speed

fields in those regions. Notice also that the region F, which is an area of convergence into the speed minimum south of the asymptote, is characterized by continuous rain from altostratus-altocumulus sheets rather than by showery cumulus or cumulonimbus precipitation.

Before proceeding to the next principle, a short digression illustrating the care that must be taken in evaluating reconnaissance reports is in order. A series of aircraft reports straddles the asymptote of convergence in the east, crossing the line between A and D. Most of these reports mention

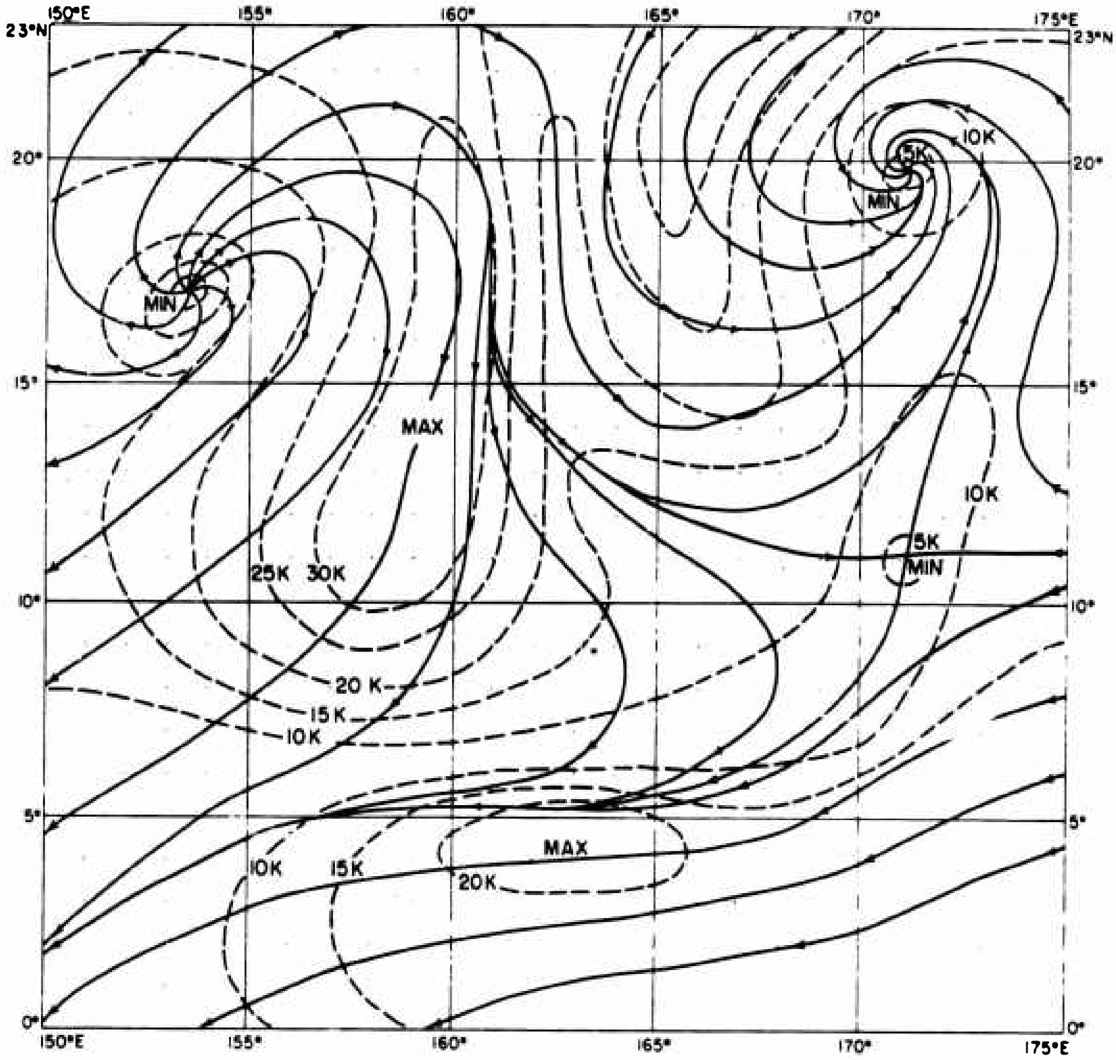


Fig. 6-15. 20,000 foot streamline-isotach analysis, Marshall Islands area, 0000 G.C.T., 13 April 1954.

heavy cumulonimbus, turbulence and heavy showers - except one, which lies exactly on the asymptote. Here 5/8ths of stratocumulus are reported. Under the older systems of reporting weather on the reconnaissance flights, an analyst receiving this report in the weather station would become suspicious either of the weather observer or of his own streamline analysis. Note, however, that under the new system of reporting, the observer is able to show that while at the point of observation the predominant cloud is stratocumulus, he is surrounded by cumulonimbus "in all quadrants". Evidently we have at this position one of the "plates" of stratocumulus which are frequently found in areas of widespread showers; they seem to develop during the rain-out of a group of heavy cumulus or cumulonimbi - these plates have been discussed earlier (section 5250).

Tenth Analytic Principle. In a case where a speed minimum lies across or away from an asymptote instead of along it, at 1500 feet, the speed minimum is usually a reflection of more active convergence aloft between the 10,000 and 30,000 foot layers. In such cases, the precipitation will be in the form of steady rain from altostratus-nimbostratus or altostratus-altocumulus sheets (an alto-system) depending on the intensity of the upper convergence.

Discussion. This point is illustrated by the regions C on figure 6-13. At 1500 feet north and east of this area, (region F), there is weak speed convergence into the speed minimum. This, however, is not the synoptic entity most strongly correlated with the weather. The 20,000 foot field of motion, shown on figure 6-15 is much better correlated with the middle and upper cloud and with the precipitation from the former An asymptote of convergence at 20,000 ft. lies above the regions C and there is strong speed convergence to the north. This asymptote is not an "equatorial front". Rather it is part of a wave system belonging to the upper tropical troposphere. Note that the whole of the middle and high cloud system follows the convergence patterns at 20,000 feet rather well in this example; note particularly that a secondary area of "bad" weather is associated around E with an upper level cyclone.

6400. CONTINUITY AND THE VORTICITY FIELD.

The fact that "good" and "bad" weather are associated with different circulation patterns, mentioned as an empirical discovery of last century in section 6100, has been refined in sections 6200 and 6300. The second empirical discovery of last century, that the circulation patterns have some degree of persistence, and are recognizable from day to day as moving systems on synoptic maps, requires similar refinement. The former refinement depends upon an understanding of the relationship of the divergence field to the weather; the latter depends upon an understanding of the relationship of the vorticity field to continuity.

The use of the vague term "circulation pattern", carries with it implications that rotatory motions are somehow involved in the synoptic entities which the meteorologist traces on his maps. The best, though not the only measure of the sense and magnitude of the rotation of individual fluid particles is the vertical component of vorticity. If we compute the vorticity field from a wind map by methods similar to those already described, we will obtain a pattern of lines showing maxima (positive) and minima (negative) of the values of the vertical component of vorticity. On such maps, persistent broad regions in which the vorticity attains maximum and minimum values are

easily recognizable; furthermore these maxima and minima, in most cases, correspond to recognizable synoptic features on the wind map, such as cyclones, anticyclones, troughs and wedges. Usually a maximum of vorticity will correspond to a cyclone or trough in the Northern Hemisphere, and a minimum to an anticyclone or ridge. Intensification of a cyclone (in the Northern Hemisphere) will be accompanied by a rise in the maximum value of the positive vorticity associated with it. Similarly, in middle latitudes the building up of a high pressure area is frequently accompanied by an increase in anticyclonic vorticity in the lower layers of the atmosphere over the same region. It follows that the forecaster using such models as cyclones anticyclones, troughs, ridges and cols can check his qualitative impressions quantitatively by means of spot computations of the vorticity. Even in high latitudes the value of such spot checks if made, not on contour or pressure maps but on wind maps, may be very great. For example, if a meteorologist suspects that a frontal wave is developing in a certain region, the fact that cyclonic vorticity is increasing in this region can be rapidly checked by a few spot computations on a wind map covering the suspect area. In tropical meteorology vorticity computations help not only in checking the rate of intensification or damping of cyclonic and anticyclonic systems but also in establishing the continuity of individual systems from level to level. In figure 6-16 and 6-17 for example, two streamline maps are shown. The map

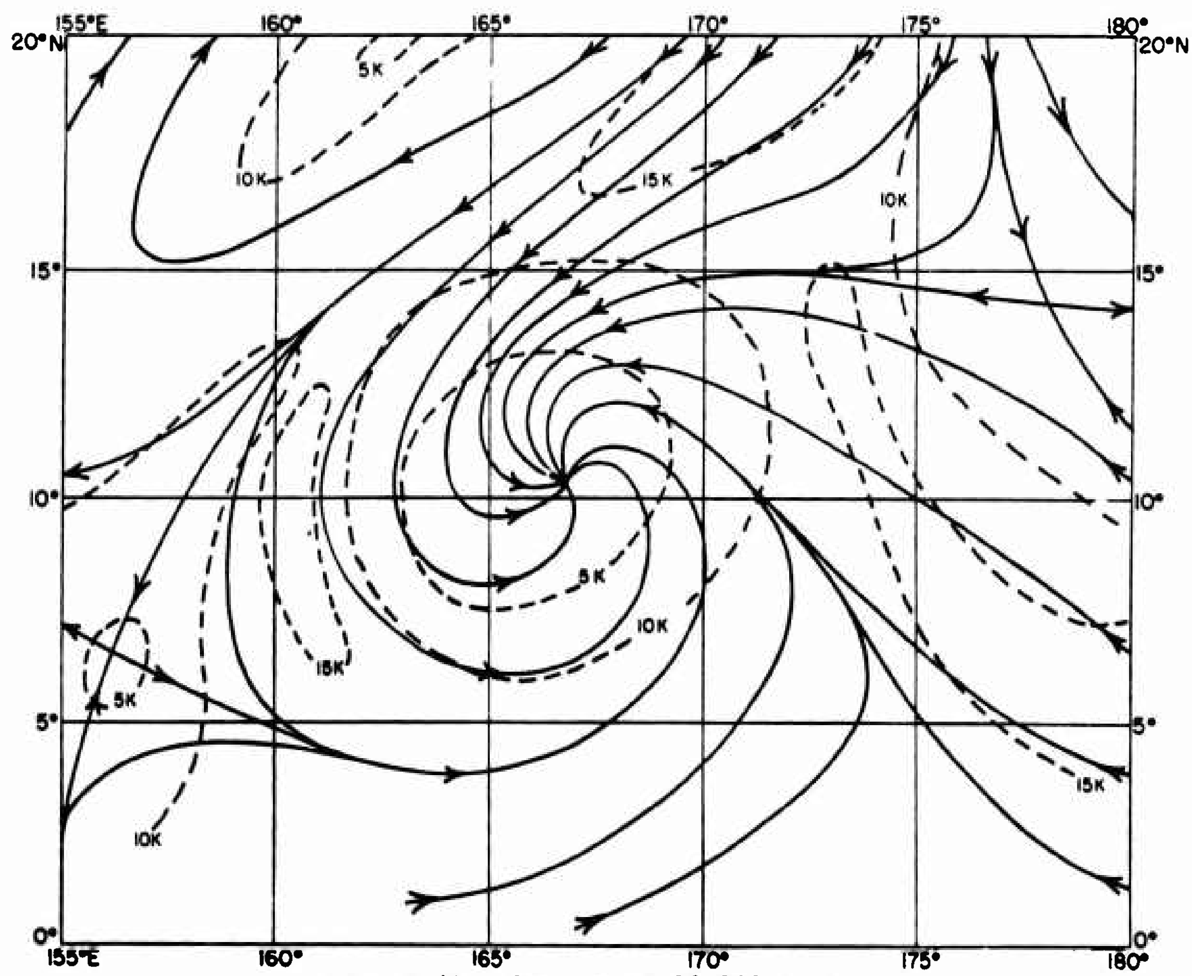


Fig. 6-16. Cyclone at 20,000 feet.

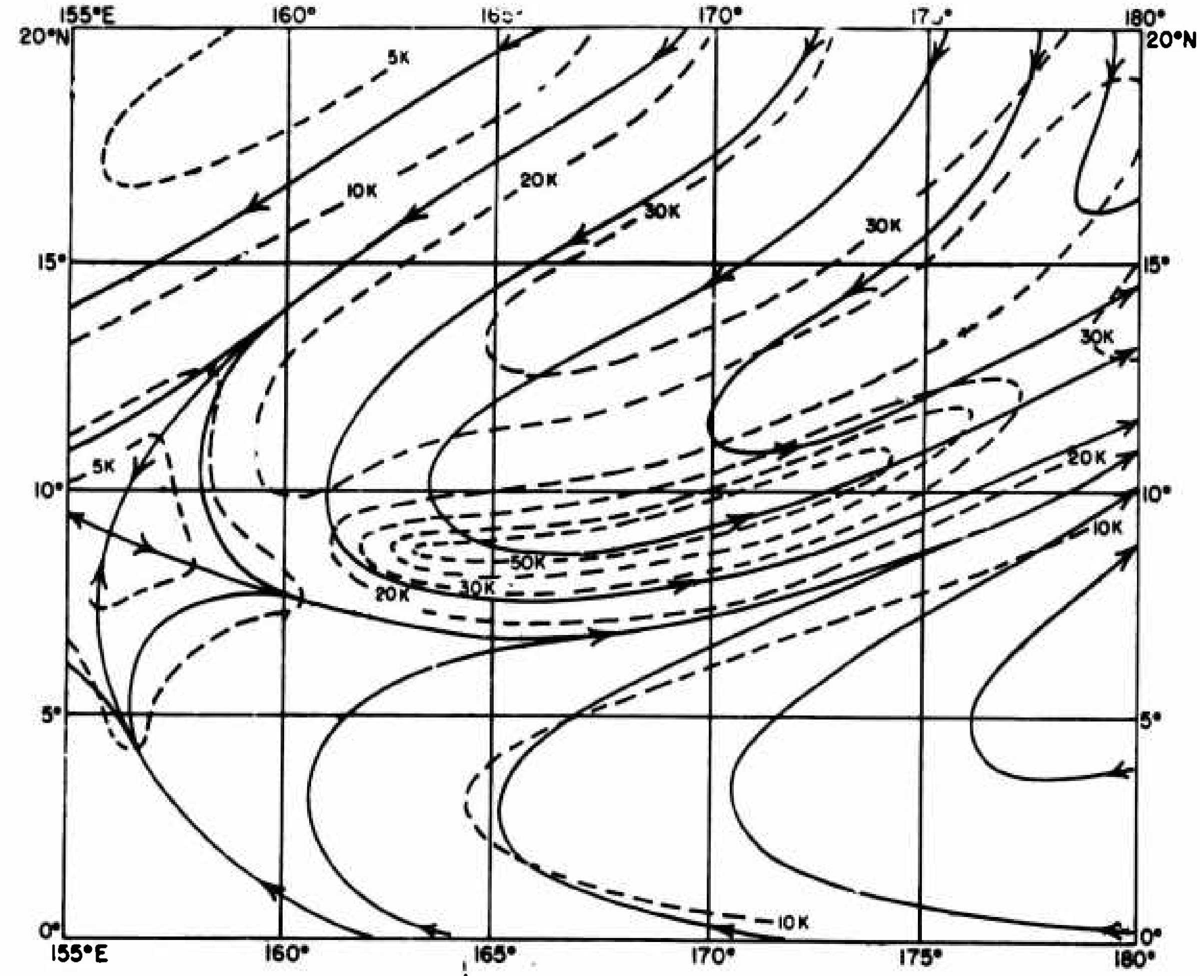


Fig. 6-17. Trough at 30,000 feet.

at 20,000 feet shows a well developed cyclone with an easily identifiable singular point; the map at 30,000 feet shows that an open "trough" is located above this cyclone. Superficially it might be thought that the system is more intense at 20,000 feet than at 30,000; computation at several points shows, however, that the vorticity at 30,000 feet in the system is twice to three times as great as at corresponding points on the 20,000 foot analysis. The system must therefore be regarded as one which increases in intensity aloft. Here the vorticity computation overcomes the natural tendency to be impressed by a cyclonic singular point; this tendency exists also in dealing with contour maps where one is inclined to believe that a closed low is always more intense than a trough. In fact, in the middle and upper atmosphere the vorticity along a trough axis is often many times greater than that of a cyclone in the lower layers. The vorticity computations may also act as a check on the common impression that, when the singularity in a cyclone disappears at a given level, the system is losing intensity. In general this is true in middle and high latitudes; however, in the tropics, upper level systems containing cyclonic singularities will often lose these singularities as the system moves into the region of the jet stream. The inexperienced analyst may get the impression under such circumstances that the upper level cyclonic system has vanished. Vorticity computations, however, will show that the maximum of cyclonic vorti-

city still exists and is travelling as an entity toward the north. On the wind map it may appear only as a "divided jet" in middle latitudes. The vorticity maximum, however, can be traced.from day to day without change in intensity or even, in some cases, with an increase in intensity in the period during which the cyclonic singularity is disappearing. Continuity both in space and time, then, is best maintained by considering the underlying vorticity field; this field has a greater degree of permanence, at least in pattern, than have the various synoptic models used on the streamline maps and described in section 4300.

There are good theoretical reasons for maintaining that the vorticity pattern has a greater degree of permanence than the synoptic entities used in tropical meteorology (on streamline maps) or in high latitude synoptic work (on contour maps). There are also good reasons for connecting the divergence and vorticity fields. At present theoretical work on vorticity, leading to simplified mathematical expressions suitable for calculations on electronic computors, is being actively pursued and it is hoped by these means to issue computed forecasts of changes in height of certain pressure surfaces. These investigations have hardly reached the stage where they influence the work of the ordinary weather station. Nevertheless, the forecaster who can construct good wind analyses may make qualitative use of many of the concepts used in this work.

7000. TROPICAL CYCLONES

The term, "Tropical Cyclone", is usually defined as a cyclonic storm of great intensity that originates in the tropics over the oceans. In this text, however, the term is used to refer to cyclones of any intensity, which exist near the surface of the earth, over the tropical oceans. In conformity with current regulations of the United States weather services the terms "Typhoon" and "Hurricane" are reserved for storms having maximum surface winds of 64 knots or greater The term "Tropical Storm" is reserved for storms having maximum surface winds of 34 through 63 knots; tropical cyclones of lesser intensity are called "Tropical Depressions".

There are many regional names which have been applied to the more intense varieties of these cyclones. For example, in the West Indies and the Caribbean they are called hurricanes, in the North Pacific, typhoons; the name "Baguio" applies in the Philippines: "El Cordonazo de San Francisco" (The Lash of St. Francis)is the name used along the west coast of Mexico, and the name "Willi Willi" is applied to the intense tropical cyclones over the Indian Ocean to the west of Australia.

While some of these names are more descriptive than others, none of them convey an adequate picture of the winds, seas and floods created by these cyclones. In dealing with tropical cyclones, a meteorologist frequently finds himself issuing forecasts which have a great significance in terms of human lives and property.

As the name implies, the low-level winds in tropical cyclones always blow cyclonically around the center, i.e., clockwise in the Southern Hemisphere and counterclockwise in the Northern Hemisphere. This may seem elementary, but it is a point often confusing to the forecaster extending his analysis across the equator for the first time.

The forecaster is most seriously concerned with the most intense variety of tropical cyclones i e., those classed as Hurricanes or Typhoons. These are characterized by extremely strong and gusty surface winds, (frequently over 100 knots), heavy squally rain and a relatively calm area near the center, known as the "Eye".

7100. LIFE CYCLE OF TROPICAL CYCLONES.

McDonald (1942) and Dunn (1944) divided the life cycle of tropical cyclones into four stages. We have followed this precedent, with certain modifications. Of course, there are no clear demarcations between the stages described.

7110. The Incipient or Formative Stage.

This stage begins when the vortex-neutral-point pair first appears in the low-level wind field. In the case of cyclones which are destined to intensify into tropical storms, current knowledge would indicate that this formation

always occurs over the ocean and is the product of a normal wave to vortex transition (section 4344). This development most frequently occurs in areas of relatively flat pressure gradient and light wind. In the incipient stage, it may be impossible to detect the cyclone as a low pressure center, and only the winds below 10,000 feet may be affected. The vast majority of these vortices either disappear within the tropics or pass into high latitudes without significant development. Those vortices which eventually do develop into tropical storms may remain in the incipient stage for several days, a week, or longer.

One of the first indications that a vortex has formed in the easterlies is the appearance of a west wind at low latitudes in an area where easterlies normally prevail. When wind observations from the equatorward side of the vortex are not available, it may be impossible to determine when the transition takes place, and the system may still be identified only as a wave in the easterlies long after the vortex has formed.

At first the wind speeds in the cyclone are not significantly different from those in the surrounding area. Often, there is a large area of very light and variable winds around the center. If there is continued development, the wind speeds increase to 30 knots or more within a narrow ring surrounding the center. The diameter of this ring may vary from several hundred miles, in very large, immature cyclones, to 60 miles or less in small intense cyclones.

7120. The Intensification or Immature Stage.

This is the period during which the cyclone undergoes the major part of its intensification from an incipient vortex to a tropical storm or typhoon (hurricane). The intensification may take place gradually over a period of several days, or it may occur almost explosively within a 24-hour period. During this stage, the cyclone becomes clearly evident in the pressure field. The cyclonic circulation extends both horizontally and vertically.

The maximum speed ring becomes more clearly defined in the isotachs and gradually decreases in diameter. In the larger cyclones this ring may contract from a diameter of several hundred miles to 60 nautical miles or less, during the deepening stage. As the storm intensifies, isotachs for progressively higher speeds appear within the maximum speed ring, and, since the speeds within the eye remain relatively light, a rapid steepening of the isotach gradient appears on the inner side of the maximum speed ring. At the same time, the area covered by winds above 25 knots, beyond the maximum speed ring, slowly expands.

During the deepening stage well-defined asymptotes, spiraling inward toward the center, appear in the streamlines. The "eye" usually develops at this stage, and the effect of the cyclone on clouds and weather becomes clearly evident. Cumulus clouds continue increasing in amount and vertical extent and become arranged in bands along the asymptotes, merging into a solid mass which rings the "eye" (see "Typhoon cloud" in section 5260). Multiple-layer middle and high clouds increase in amount, often merging with the cumuli. Showers and squalls increase with the cumulus development, and rain becomes widespread near the center.

7130. The Mature Stage.

This stage may be defined as the period during which the storm remains at or near its maximum intensity. There is a great range in both size and intensity in this stage. Some storms reach maturity as small intense cyclones; others may not reach maturity until they have developed into the largest of typhoons (hurricanes); all varieties of sizes and intensities exist in between. This stage lasts from a few hours to a week or longer. It is characterized by relatively constant pressure at the center, while the surrounding isobars are gradually spreading. The area affected by strong winds may increase slightly. The area of associated clouds and weather is usually at its maximum and the eye is most clearly defined at this stage.

7140. The Stage of Decay.

The stage of decay is the period during which the storm either assumes extra-tropical characteristics or fills, diminishing in intensity until it loses its identity. Those storms which move inland may fill very rapidly, especially if the terrain is rough. In the case of storms which recurve into high latitudes there is a gradual transition to extra-tropical characteristics, i.e., the band of maximum winds and the eye become less clearly defined, and polar air may be drawn into the cyclone at low levels. Weather and cloud distribution in this stage depend largely upon orographic effects and in some regions, such as the Philippines, the rainfall reaches a maximum during the early part of this stage.

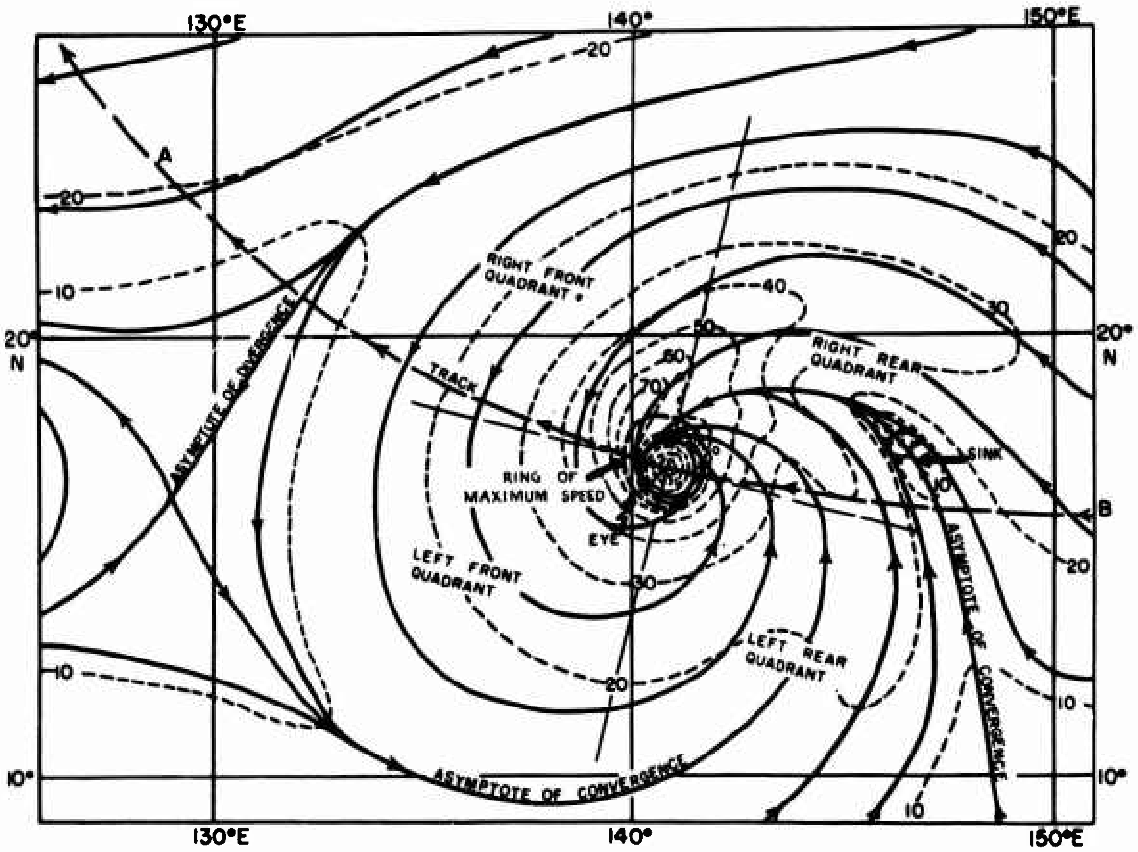


Fig. 7-1. The components of a mature tropical cyclone.

7200. THE STRUCTURE OF TROPICAL CYCLONES.

To make the most efficient analysis of available data in the vicinity of tropical cyclones, the forecaster must be familiar with the normal wind, pressure, temperature, clouds and weather patterns associated with these storms. It is not inferred that all tropical cyclones are exactly alike. On the contrary, there are great variations between storms. However, there are certain general features which appear with sufficient frequency to predominate in the mean patterns. These features serve as a valuable guide when reconstructing the picture of an individual tropical cyclone from sparse data.

Since the meteorological elements are not distributed uniformly throughout all sections of the cyclone, it has become customary to describe these storms in terms of the four quadrants separated by the line along which the center of the storm is moving and the normal to this line at the cyclonic center (Fig. 7-1). Of course, in nature there are no clearly defined demarcations between the quadrants.

7210. The Horizontal Wind Field.

Data sufficient to describe the wind field completely and accurately in a single tropical cyclone have never been obtained. However, Hughes (1952) has summarized a large number of carefully selected wind observations from low-level weather reconnaissance flights in and around tropical cyclones, and E. S. Jordan (1952) combined all available rawin reports, taken within the circulation of tropical cyclones of storm intensity, to obtain a generalized pattern of the upper wind circulation.

7211. Low-Level Winds. Hughes found the distribution of low-level winds to be the same, except in scale, in both large and small storms. His figures apply only to the region beyond a radius of 30 nautical miles from the center and do not pertain to the eye of the storm.

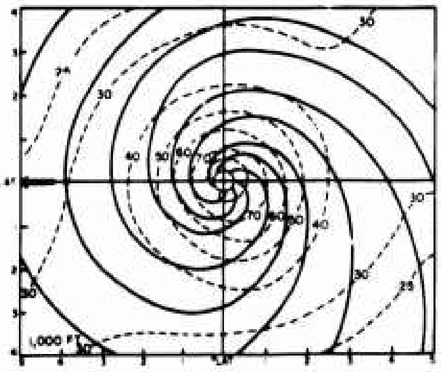


Fig. 7-2. Mean low-level (near 1,000 ft.) streamlines and isotachs in large mature tropical cyclones. Wind speeds in knots. (After Hughes, 1952).

Figure 7-2 illustrates the mean streamline and isotach patterns found by Hughes, in large, mature, Pacific typhoons. Notice that the strongest winds are in the right rear quadrant and that the isotachs near the center have a horseshoe shape, indicating a ring of maximum winds around the center. Hughes did not have data to substantiate the innermost isotachs. However, this pattern is frequently observed and the figure is believed to be representative. The mean diameter of the maximum speed ring in large mature storms appears to be about 40 nautical miles.

On the inner side of the maximum speed ring, the isotach gradient is extremely steep and probably fairly uniform in all quadrants. Within the eye, winds are relatively light, and, of course, the speed is zero at the singular point. On the other side of the maximum

speed ring, the isotachs also appear to be roughly concentric in the mean. However, in individual cyclones, the speed maxima associated with separate, converging air streams within the cyclonic circulations produce numerous perturbations of the standard isotach pattern.

Hughes' results indicate that, in the mean, the diameter of the area affected by hurricane winds (64 knots or greater) is about 120 nautical miles. This, of course, varies greatly; according to Dunn (1944) it may be in excess of 100 miles in large storms or as small as 35 miles. Gale winds (30 knots) sometimes cover an area of 500-800 miles or more. The maximum extent of strong winds is usually in the direction of the major subtropical anticyclone in the area. This is most frequently to the right of the line of movement of the cyclone.

The average of maximum, low-level wind speeds is indicated, in figure 7-2, as being slightly greater than 90 knots. Speeds greater than 140 knots have been recorded and it seems reasonable to assume that speeds near 200 knots may be attained at altitudes of several hundred feet above the surface.

The mean streamlines spiral inward toward the center in all quadrants, but those in the left rear quadrant have the greatest angle of inflow. Figure 7-3 illustrates the mean "in-curvature" field. This figure seems to indicate that the air in the left rear quadrant was approaching the storm center faster than air from the other quadrants. However, when only the components relative to the moving center are considered, it is found that, in moving a given radial distance toward the center, air from the right front quadrant travels over a much shorter spiral trajectory and requires about half as much time as air from the left rear quadrant.

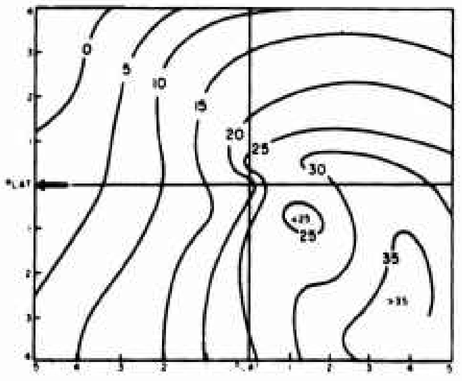


Fig. 7-3. The mean in-curvature field, in degrees, near the 1,000 ft. level (Hughes, 1952) in large mature tropical cyclones.

The strong asymptotes, which are characteristic of the streamline patterns in the intense stages of these cyclones for levels up to 10,000 feet, are completely lost in the averaging process used to determine the mean patterns. There are usually at least two asymptotes of convergence, spiraling inward toward the center, which can be easily located in the streamlines. The cloud structure often indicates that many weaker lines of convergence also exist. The stronger asymptotes of convergence often contain numerous tiny vortices called "sinks", which form and dissipate rapidly while moving along the asymptote toward the storm center. These sinks account for many of the apparently inconsistent winds observed within the circulation of large tropical cyclones. They are usually associated with very large cumulus or cumulonimbus clouds, which sometimes adopt an arrangement similar to that near the eye of a small cyclone. Aerial weather observers have been known to mistake one of these sinks for the center of the storm.

Depperman and others recognized these asymptotes and described them as "fronts" many years ago. Of course, it was realized that they differed from

the fronts of high latitudes.

An asymptote of divergence is characteristic of the forward edge of the cyclonic circulation. This accounts for the general decrease in normal cumulus cloud cover which frequently precedes the storm.

<u>7212. Upper-level Winds.</u> E. S. Jordan (1952) summarized approximately 130 wind soundings, all of which extended to 30,000 feet, 88 of which extended to 45,000 feet. All were located between a distance of 2 degrees and 6 degrees of latitude from a mature cyclonic center.

Mean streamlines and isotachs for 7,000 feet and 45,000 feet, reconstructed from Jordan's resultant wind data, are illustrated in figure 7-4. Notice that,

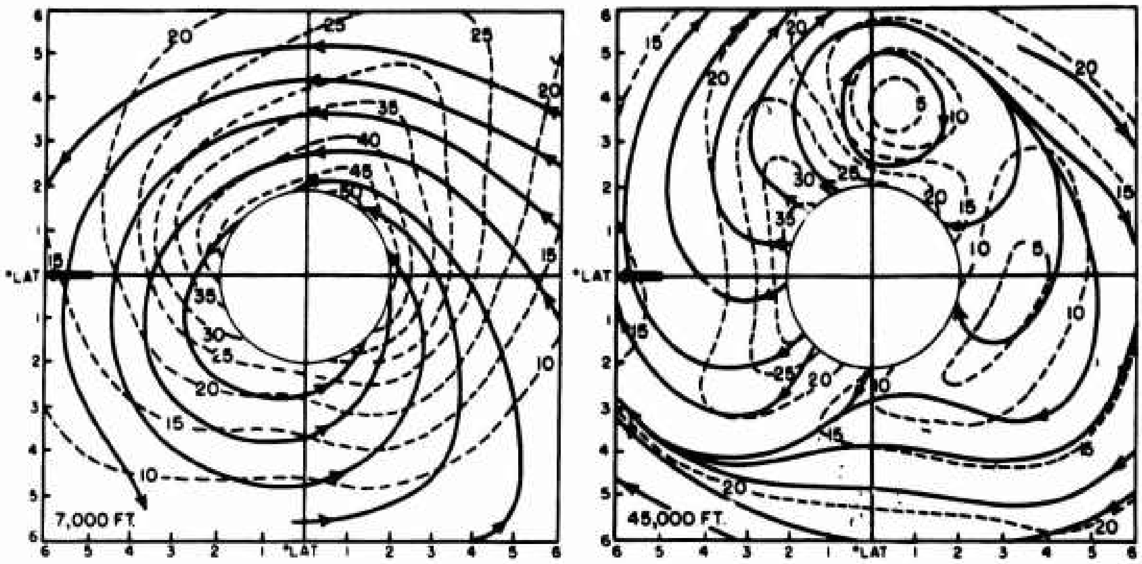


Fig. 7-4. Streamlines and isotachs for the resultant winds at 7,000 feet and 45,000 feet in mature tropical cyclones. Wind speeds in knots. (After E.S. Jordan, 1952)

at 7,000 feet, the in-curvature of the streamlines is much less pronounced in all quadrants than those for the lower levels shown in figure 7-2. There is actually a component away from the storm center in the forward part of the cyclone at the 7,000 foot level. The maximum speed ring appears to be near the inner limit of the data and the maximum winds appear to be lighter than those found at lower levels by Hughes. However, these two points can not be definitely stated, since the picture is not complete at either level, and data from cyclones of many sizes were, of necessity, included in Jordan's summary.

At 45,000 feet the resultant wind streamlines, while obviously still under the influence of the cyclone, show a complex flow pattern which is predominantly anticyclonic. The only cyclonic curvature in the streamlines appears near the inner limit of the analysis in the rear half of the storm. It appears that the area and strength of the cyclonic circulation decreases rapidly with altitude.

In the past, there has been much speculation concerning the vertical extent of mature tropical cyclones. It is now, however, well established that they often extend at least to 45,000 feet; so far as is known they have little effect on the stratospheric easterlies which have their base at the tropopause.

At 45,000 feet the strongest winds are located ahead of the storm center and are directed away from it. This pattern gives a good indication of the errors which can be made when locating a cyclonic center on the basis of one or two high level wind observations. Similar complex patterns may be found at lower levels with tropical cyclones which have not yet extended to the upper troposphere. It is not inferred that all tropical cyclones form first at the lower levels. Numerous storms appear to have resulted from the downward extension and intensification of an upper level cyclone. Weak, low-level cyclones have also frequently been observed to intensify rapidly when located directly beneath an upper level cyclone, and, with the sparse data normally available in the areas of cyclone intensification, it is difficult to determine which of the two processes has taken place.

While little is known about the slope of the axes of tropical cyclones, they are generally assumed to be nearly vertical. The observed cloud distribution and the fact that there are no significant air mass differences tend to support this idea. The few accounts of tropical cyclones having great vertical slope have probably resulted from an analyst connecting two independent cyclones one at low levels and the other at upper levels. This is a common error when the analysis is performed only on charts for the mandatory pressure surfaces. without reference to wind time-sections. In any case, when one considers that the diameter of the eye of a large, mature hurricane is often greater than the entire vertical depth of the storm the slope of the vertical axis seems unimportant. Having studied numerous published cross-sections (all greatly exaggerated in the vertical) of mature tropical cyclones, the forecaster may have learned to think of the eye of the storm as being shaped like a very narrow funnel, while the actual appearance bears more of a resemblance to a broad bowl (Fig. 7-6).

<u>7213. Horizontal Divergence.</u> It has long been known that strong horizontal convergence exists in the low-level winds of tropical cyclones, and divergence has long been assumed to exist in the upper level winds. The papers by Hughes and Jordan, referred to above, shed some light on the field of divergence in mature storms. Both presented figures on the radial component of the wind within the cyclonic circulation. The radial velocity of the wind is an expression for the magnitude of the wind component toward, or away from, the center of the vortex and provides a means of comparing, in a general way, the convergence at one level with that at others. In all quadrants, at low levels, Hughes found the radial component directed inward and the radial speed increasing inward to a maximum near the ring of maximum wind speeds.

E. S. Jordan found that the mean inflow at 7,000 feet was about 30 percent of that which Hughes found at 1,000 feet. The areas of inflow and outflow were nearly equal in the layer between 10,000 and 30,000 feet and above this layer the outflow exceeded the inflow. At all levels the inflow was greatest in the rear sections and the outflow greatest in the forward sections. At 45,000 feet, there was a component of over 30 knots away from the center in the forward section. Thus, we have a picture of strong convergence in the lower 10,000 feet, strong divergence above 30,000 feet and a neutral layer in between.

7214. Vertical Motion. Few, if any, direct measurements of the vertical motions in tropical cyclones have ever been made. However, computations by indirect methods and observations of the types and distribution of clouds give some indications of the field of vertical motion within these storms. Hughes (1952) determined the mean field of vertical motion near the 1,000 foot level by computing the horizontal divergence of the mean winds for that level. At very low levels, with constant density, the patterns in both fields, divergence and vertical motion, may be considered identical (see section 6210). He found that the rate of convergence and upward motion increased inward, from the outer limits of the circulation, to a ring of maximum values which surrounded the center and had a diameter slightly larger than that of the ring of maximum wind speeds (Fig. 7-2).

In seetion 7213 we saw that the only outflow which could disperse the surplus of air, brought into the cyclone by convergence in the low levels, existed above 30,000 feet. Therefore, we can assume that upward motion extends at least to that level and probably much higher. The distribution and vertical development of cumulus clouds indicates that upward motion strongly predominates in a ring surrounding the eye and that, in the outer regions of the circulation, the upward motion is concentrated in the major asymptotes, with large areas of only slight upward motion lying between them. At low levels Hughes found a weak maximum of subsidence at a distance of 180 nautical miles from the center, in the right forward quadrant. This would be associated with the asymptote of divergence which is frequently found ahead of the storm.

Charles L. Jordan (1952) summarized 45 aircraft and dropsonde soundings, of which 35 were made in typhoon eyes and 10 in storm circulations from 50 to 200 nautical miles from the cyclonic center. From his mean soundings and the visual data obtained by aerial reconnaissance, he deduced that the downward motion within the eye does not extend to the surface but often reaches the 3,000 feet level, going below that only in the more intense storms. His data also suggested a zone of vertical and lateral mixing with its top between 10,000 and 20,000 feet and its lower limit often extending nearly to the surface. Jordan's findings are in agreement with the typhoon model advanced by Riehl (1951).

7220. The Pressure Field.

From the time a tropical cyclone enters the deepening stage until it dissipates completely, it is associated with a clearly defined low pressure center which extends from the surface to the upper levels of the storm. Isobaric and pressure contour analyses are therefore important tools of the hurricane or typhoon forecaster. Since the isobars are seldom symetrical about the center of the cyclone, great care must be exercised when attempting to pinpoint the center on the basis of pressure data. Generally speaking, the isobaric pattern resembles that which would be obtained by superimposing an asymetrical low pressure center upon the normal isobars of the area. In the Northern Hemisphere, the pressure gradient is generally strongest to the right of the center, or in the direction of the major anti-cyclones, and weakest to the left of the center, in the direction of the equatorial trough. The isobars in the outer regions of the cyclone are usually further deformed by weak pressure troughs which are associated with the major asymptotes in the storm circulation.

The pressure gradient along the line of movement of the center can be computed from the barograph trace when the rate of movement of the storm center is

known. Gradients computed in this manner by Deppermann, (1939) indicate a mean fall of 1 mb per mile on the forward side of typhoons having a minimum pressure near 960 mbs. Gradients more than twice this strong sometimes occur. Dunn (1944) cites a case in which the pressure fell approximately 68 mb in 90 minutes ahead of a hurricane in the central Caribbean. Here, the rate of movement of the storm was not taken into account.

Numerous attempts have been made to correlate the central pressure, or the average pressure gradient between the center of the storm and an arbitrarily selected sea level isobar near the outer limit of the cyclone, with the maximum surface wind within the storm. The Typhoon Post-Analysis Board, Anderson Air Force Base, Guam (1952), in an empirical study of 230 typhoon reconnaissance flights, found a close relationship between the central pressure and the maximum surface winds, when a latitudinal factor was introduced. The board also found a relatively good correlation between the sea-level pressure and the 700 mb height at the center of the cyclone. A working table showing the normally corresponding values of sea-level pressure and 700 mb. height, and the latitudinal variation of maximum surface wind speed with given central pressures, is presented in Table 7-1. These figures appear to be suitable for forecasting use in the absence of observational data.

Minimum surface pressures below 950 millibars frequently occur in mature hurricanes, and record surface pressures below 890 millibars have been measured. Pulsations in the surface pressure, which cause oscillations in the barograph trace have been observed in hurricanes and typhoons on numerous occasions. These fall into two classes, i.e., short period oscillations occuring at 6 second to 3 minute intervals and long period oscillations having a period on the order of one-half hour. The latter may have an amplitude of more than a millibar, and, under certain circumstances, their first appearance at a station could be mistaken for the passage of the minimum pressure of the storm. The period of either type of oscillation is often irregular.

Kinks have sometimes been recorded in the barograph traces taken in mature tropical cyclones. These differ from the oscillations in that they are usually not repeated and their magnitude is greater, i.e., one to four millibars. These kinks sometimes appear to travel with the storm but not necessarily at the same speed as the storm center. They are probably the concomitants, in the pressure field, of the "sinks" in the wind field mentioned in section 7211.

7230. The Temperature Field.

The temperature distribution in tropical cyclones, while of great interest to the theorists, is of little interest to synoptic meteorologists. Early writers on the subject attached great importance to reports of temperature rises during the passage of the eye of the cyclone. It is now believed that all such temperature rises can be attributed to local orographic or insolational effects and are not characteristic of the storms themselves.

The few high level soundings taken within the eyes of hurricanes indicate that the temperature in a layer roughly between 6,000 and 50,000 feet is generally 5° C to 15° C higher than that at corresponding levels in the surrounding area.

There has been much speculation, and very little observational data, on changes in height and character of the tropopause above tropical cyclones. The

SFC PRESS	700 MB. HEIGHT	MAXIMUM SURFACE WIND Latitude 5°	10°	15°	20°	25°	30°	35°	40°	45°
1000	10130	60	57	54	51	48	45	41	38	35
995	9990	74	70	66	62	58	55	50	47	43
990	9850	85	80	76	72	67	63	58	54	49
985	9710	95	90	85	80	75	70	65	60	55
980	9570	104	99	93	88	82	77	71	66	61
975	9430	112	107	100	95	89	83	77	71	65
970	9290	120	114	107	101	95	89	82	76	70
965	9150	128	121	114	108	101	94	87	80	74
960	9010	135	127	120	113	106	99	92	85	78
955	8870	141	133	126	119	111	104	96	89	82
950	8730	148	140	132	124	116	109	101	93	86
945	8590	153	145	137	129	121	113	105	97	89
940	8450	159	151	142	134	126	117	109	101	92
935	8310	165	156	148	139	130	121	113	104	95
930	8170	170	161	152	143	134	125	116	107	98
925	8030	175	166	157	147	138	129	120	111	101
920	7890	180	171	161	151	142	133	123	114	104
915	7750	185	175	165	156	146	137	127	117	107
910	7610	190	180	170	160	150	140	130	120	110
905	7470	195	184	174	164	153	143	133	123	113
900	7330	199	189	178	168	157	147	136	126	115

Table 7-1. Normally corresponding values of sea-level pressure and 700 mb. height, and the latitudinal variation of maximum surface wind speed with given central pressures, in typhoons. (Typhoon Postanalysis Board, Anderson Air Force Base, Guam, 1952)

few available soundings taken within the circulation of mature tropical cyclones indicate that the level of minimum temperature slopes upward from the outer limits of the storm toward the center, the total change in height being on the order of 5,000 feet. The temperature at the base of this inversion appears to decrease slightly toward the center.

Other temperature inversions or abrupt changes in lapse rate also appear at high levels within the cyclone and these have led to much controversy concerning multiple tropopauses. Such arguments are mainly of an academic nature and are believed to have little bearing on forecasting problems at present.

7240. Cloud Distribution.

Dunn (1944) describes the cloud sequence that accompanies an approaching tropical cyclone as similar to that in advance of a warm front. First, cirrus appears, then thickens to cirrostratus and later to altostratus and altocumulus with large cumulus extending upward through the upper cloud layers. Finally, the cumuli become an almost solid mass.

Near the outer periphery of the cyclone, cumuliform clouds may be normal, or slightly below normal, in amount and vertical development, for the area. Within the circulation of the storm these clouds tend to become arranged in

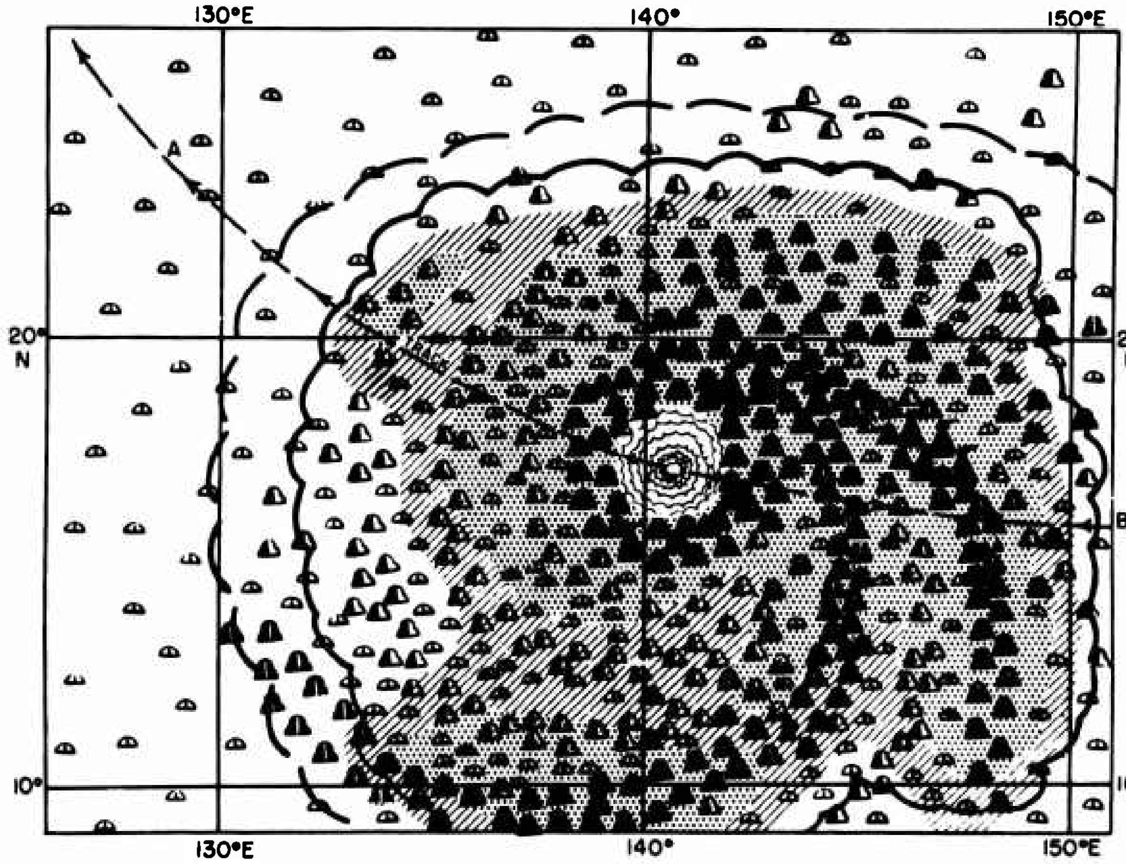


Fig. 7-5. Typical cloud distribution associated with the wind pattern illustrated in figure 7-1. For an explanation of the symbols see section 5310.

bands along the streamlines. The larger cumuli are concentrated in bands along the major asymptotes which spiral cyclonically inward toward the storm center. Progressing inward along these bands, the amount and vertical development of the cumuli increases until the bands merge into the more or less solid mass of cloud, sometimes reaching to the tropopause, which forms the wall around the eye of the storm (Figs. 7-5 and 7-6). Many observers have described these bands of cumulus as concentric rings of cloud. Radar-scope photographs, however, show their spiral structure very clearly.

Fig. 7-6. A vertical cross-section along the storm track, from A to B in figure 7-6. Vertical scale in thousands of feet, horizontal scale in degrees latitude. The vertical scale of this drawing is exaggerated approximately ten to one over the horizontal scale.

Since the cloud bands lie along the streamlines, the orientation of the cloud bands, when discernable, can provide a visual means of determining the wind direction at levels between the surface and the cloud tops. Sheets of altocumulus cloud often extend hundreds of miles from the center, merging with and being pierced by, the tops of the cumulus. Cirrus sheets also extend many hundreds of miles from the storm center. There is some disagreement in the literature as to whether the cirrus clouds radiate from, and move outward from, the storm center or merely move forward in the general stream in which the cyclone is imbedded. Simpson (1954) has also presented photographic evidence of a band of cirrus spiraling cyclonically inward toward the center. In view of the complex wind patterns now known to exist near the upper limits of the cyclones it seems reasonable to anticipate a great variety of cirrus patterns, depending upon the level of cirrus formation and the vertical extent of the storm circulation.

Cloud conditions within the eye vary greatly from case to case. On some occasions the eye has been almost free of clouds, but generally there are at least small amounts of low, middle and high cloud. On most occasions the eye is filled with broken stratocumulus and cumulus with only slight vertical development. A number of observers have reported cumulus tops near 10,000 feet at the center of the eye. These small clouds are sometimes found in bands which spiral toward the center of the eye, from the inner wall of the storm.

Scattered to broken altocumulus clouds are commonly found within the eye, often at more than one level, and cirrus clouds frequently cover most of the eye.

Low cloud bases are seldom lower than 1,000 feet. However, ceiling and visibility are frequently zero in the heavy rain areas.

7250. Precipitation.

Very heavy rainfall is generally associated with mature cyclones. However, the methods of measurement are subject to such large errors during high winds that representative figures on the normal amount and distribution of precipitation in the storms can not be said to exist.

Hughes (1952) computed the rate of rainfall within rings of various radii surrounding the center of mature tropical cyclones (Fig. 7-7). His calculations are based upon the assumption that virtually all water vapor, which has been transported inward by the low level winds across a closed curve surrounding the storm center, is precipitated within the area enclosed by the curve. Rainfall figures thus derived are completely dependent upon the radial component of the wind, which is closely related to the field of divergence. Therefore the distribution of rainfall should closely resemble the divergence pattern.

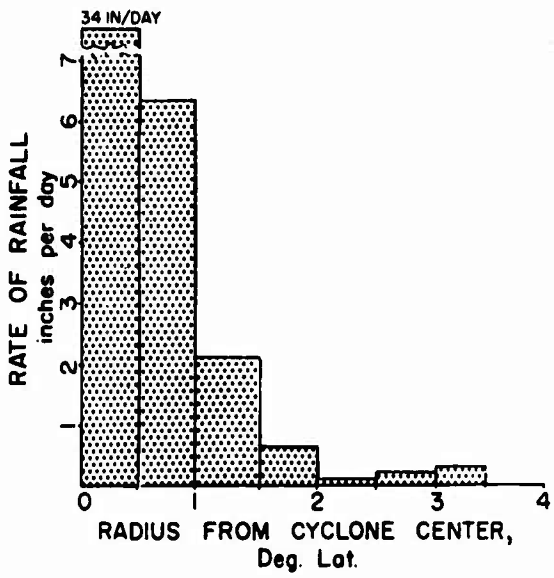


Fig. 7-7. The computed average rates of rainfall within concentric bands surrounding the centers of large mature tropical cyclones. (After Hughes, 1952).

Based upon the rainfall rates computed by Hughes, an average mature tropical cyclone moving at ten knots would produce about 11 inches of rain in 48 hours at a station located on the track of the storm center. This figure is in close agreement with the rainfall rates found by Cline (1926) in his study of Atlantic storms.

Over the open sea, rainfall is of operational interest primarily from the standpoint of its effect upon ceiling and visibility. Over land, orographic effects produce concentrations in the rainfall which often result in costly floods. Hurricane winds, forcing moisture laden tropical air up a steep mountain slope, often result in phenomenal rainfall. A fall of 88 inches was recorded during one storm in the Philippines. At the other extreme, as little as a trace has been recorded at a station in the Florida Keys which had winds up to 120 knots during the passage of a hurricane.

7260. Severe Weather Phenomena.

Adequate statistics on the occurrence of thunderstorms and tornadoes, in tropical cyclones, have not been published. Thunderstorms are frequently observed in the outer regions of the cyclones. They are reported less frequently in the inner regions of the storm, perhaps because they are obscured by the surrounding mass of clouds. Over the open sea they tend to be concentrated along the major asymptotes in the low level winds, and especially in the vicinity of the sinks on these asymptotes (section 7211). In coastal regions the location of the thunderstorms is likely to be determined by the orientation of the hurricane winds, relative to the local hills or mountains.

Tornadoes, moving with the hurricane winds, have been observed in coastal regions. Indications are that in most cases they develop over the ocean, as waterspouts, and travel inland only a few miles before dissipating.

7300. STATISTICS OF THE OCCURRENCE AND MOVEMENT OF TROPICAL CYCLONES.

Statistical information derived from past occurrences provides the forecaster with one of his primary tools. This is especially true in the case of tropical cyclones, even though data suitable for detailed statistical studies have not been available in most areas. Mitchell (1924) and Colon (1953) have published detailed studies of tropical storms and hurricanes in the Caribbean Sea, the Gulf of Mexico and adjacent regions of the Atlantic Ocean. The 1st Weather Wing, Tokyo, publishes climatological charts of tropical storm and typhoon tracks over the western North Pacific Ocean and China Sea. The Meteorological Office, Air Ministry, London (1943) published the tracks of tropical cyclones over the Indian Ocean for the period 1928 to 1937. Dunn (1951) presented monthly mean hurricane tracks for the western North Atlantic area. It is assumed that the forecaster will have access to these or similar studies which pertain to his area of interest.

Cyclones of tropical storm intensity are believed to occur over virtually all tropical seas. However, cyclones of hurricane intensity very rarely

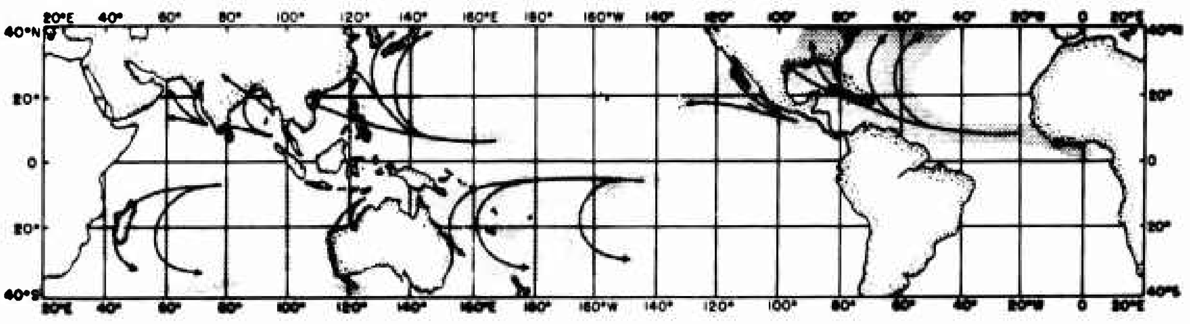


Fig. 7-8. Regions most frequently affected by tropical cyclones of storm or hurricane intensity (shaded areas) and generalized mean cyclone tracks.

occur within 5 degrees of latitude on either side of the equator. They have never been recorded over the South Atlantic Ocean or the South Pacific Ocean east of 140° W.

Figure 7-8 indicates the areas of most frequent occurrence of tropical storms, hurricanes and typhoons, and their mean tracks. The tracks are merely rough approximations and should not be used for forecasting purposes.

In the Northern Hemisphere, cyclones of tropical storm or hurricane intensity occur most frequently over the western North Pacific, North Atlantic and Caribbean area, and the eastern North Pacific, where they average 21, 10 and 8 per year respectively. In these areas the seasonal maximum occurs during August, September and October. Over the North Atlantic and eastern North Pacific areas they are extremely rare during the months of December through May. Over the western North Pacific an average of only three per year occur during these months.

In the Bay of Bengal and its surrounding area, an average of 5 to 6 hurricanes or tropical storms and 7 tropical cyclones of lesser intensity occur each year. In the area of the Arabian Sea, the averages are less than 2 storms and 6 weak cyclones per year. In these areas tropical cyclones rarely occur during January, February and March, and mid-summer storms seldom reach hurricane intensity. The greatest number occur during Spring and Fall.

Over the southwestern Pacific, Hutchings (1953) annual averages of 3.6 storms with winds over 40 knots and less than one storm of hurricane intensity. His figures indicate a well-marked concentration during the months of Demember through March and only rare occurrences in other months.

Over the western South Indian Ocean an average of 7 tropical storms or hurricanes and 4 weaker cyclones occur each year. Intense tropical cyclones also occur over the South Indian Ocean to the northwest of Australia. Little is known about their frequency of occurrence in this region but it is apparently about one per year. In all of the Southern Hemispheric regions, the greatest frequency of tropical cyclone occurrence is in the months of December through March. In the south Indian Ocean, tropical cyclones are almost unknown during the months of June through October.

In all regions where tropical cyclones occur, the number which reach tropical storm and hurricane intensity, and the monthly distribution of their occurrence, varies greatly from year to year.

7400. FORMATION AND INTENSIFICATION.

Since the winds remain relatively light during the formative stages of tropical cyclones, and the majority of them never reach storm intensity, the forecast of the initial formation is not a serious problem. The forecast of the intensification stage, however, is one of the primary problems facing the tropical meteorologist. This becomes a particularly serious matter when the intensification occurs near inhabited localities.

Forecasters working in both the Pacific and Atlantic areas have developed certain empirical rules which at present are the forecasters' primary guides to the intensification forecast. These rules, in basic form, are as follows:

(1) Intensification takes place only when the easterlies extend vertically to 25,000 feet or higher at the latitude of the vortex. This most frequently occurs when the subtropical ridge lies poleward of its normal position for the season.

(2) A decrease in the speed of movement of the cyclone is usually associated with intensification. An increase in the speed of movement is not as frequently associated with a decrease in intensity.

(3) Intensification occurs when the cyclone passes under an upper level trough or cyclone provided there is relative motion between the two. There is some indication that intensification does not take place when two remain superimposed.

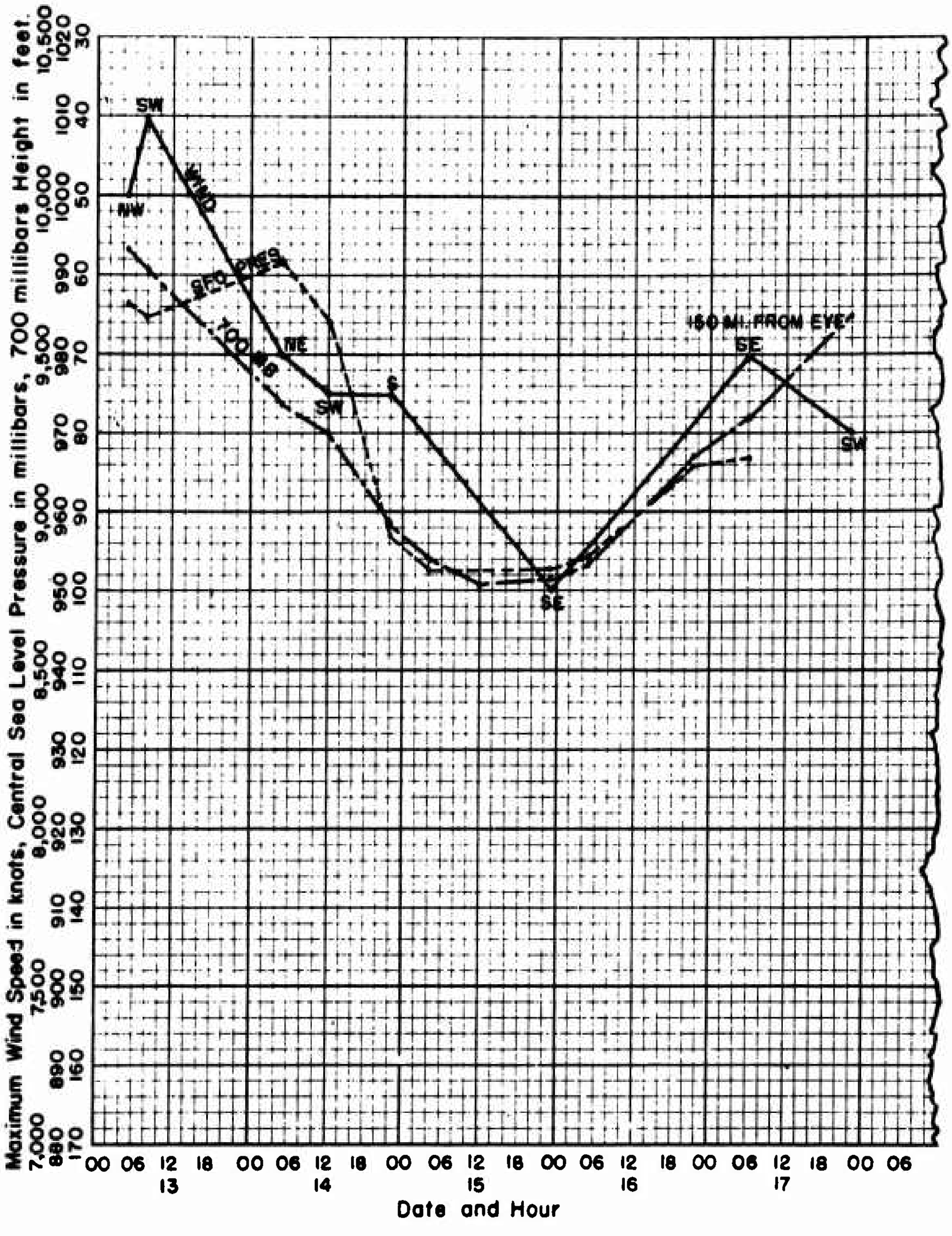


Fig. 7-9. A graph of the maximum surface wind, central sea-level pressure and central 700 mb. height in a typhoon. Letters on the wind plot indicate the quadrant where observed.

(4). Intensification is unlikely until the preceding hurricane has passed inland, dissipated or recurved through the sub-tropical ridge. There are, however, numerous exceptions to this rule.

(5). Poleward movement of the cyclone is favorable for intensification; equatorward movement is not.

(6). Intensification of tropical cyclones occurs only in areas where the sea surface temperature is 77°F. (25°C.) or higher. This is true in the mean. Its synoptic reliability has never been thoroughly checked.

(7). The advection of cold dry air into the low levels of the cyclone will cause it to lose intensity.

Extrapolation also provides a useful means of forecasting the rate of intensification for short periods. A recommended procedure is to plot maximum wind speed, minimum sea level pressure, and minimum height of the 700 millibar level on a sheet of graph paper with time as the other coordinate. Then make the forecast by extending the plotted curves, after considering the rules listed above, (Figure 7-9).

7500. DETECTION AND LOCATION.

Ideally, the cyclone may be first detected, and its location thereafter determined, by frequent aerial reconnaissance flights. However, these aircraft are not always available and, in any event, are relatively expensive. The forecaster, therefore, must be alert for evidence of cyclone formation in his routine weather data. A shift in low level wind direction from east to west, where this is not a normal diurnal occasion, is often the first clue to cyclone formation. Every area in which marked cyclonic turning in the low level winds, with time, should be carefully watched, as should those with greater than normal cloudiness, rainfall or fall in pressure. The low level wind analysis provides one of the best means of locating the cyclonic center; after intensification has begun, the sea level pressure analysis may also be useful. In using the pressure analysis for this purpose, however, the eccentricity of the isobars about the cyclone must be given consideration.

In isolated areas, reports of sea swells of abnormally long period or unusually high tides may provide the first clue to the existence of a new tropical storm or hurricane, (see Section 7800).

New, longer-range radar equipment may soon provide a practical means of locating and tracking tropical cyclones. Even at present, radar provides one of the best short-range methods of observing their movement.

Research is still being conducted upon the practicability of seismic, sferic and other methods of detection and location of cyclones. These techniques, however, are not yet at the stage where they can become a part of the routine weather station operation.

7600. MOVEMENT OF TROPICAL CYCLONES.

In the mean, there is a tendency for tropical cyclones to follow a hyperbolic or parabolic curve away from the equator; however, departures from this type of track are frequent and of great variety.

7610. Theoretical Aspects.

Numerous theories have been advanced to explain the cyclone tracks of the past and predict those of the future. Observational data have never been sufficient to prove or disprove most of them. A few theoretical concepts have found limited practical application, but, for the most part, the forecaster must rely upon empirical knowledge and extrapolation when predicting the movement of tropical cyclones.

There is no doubt that, at the present stage of development of tropical meteorology, forecasting the tracks of cyclones is an art. Among experienced forecasters, some are much more successful than others using the same data; often the most successful are at a loss to explain the methods they employ. A critical examination of the art, however, shows that the successful practitioners use, either consciously or unconsciously, reasoning based upon analogies between hydrodynamic flow (as in liquids or gases) and the behavior of electric and magnetic fields. Many empirical notions, such as that of "steering", which are used in discussing the problem of cyclone movement, are also based upon the analogy.

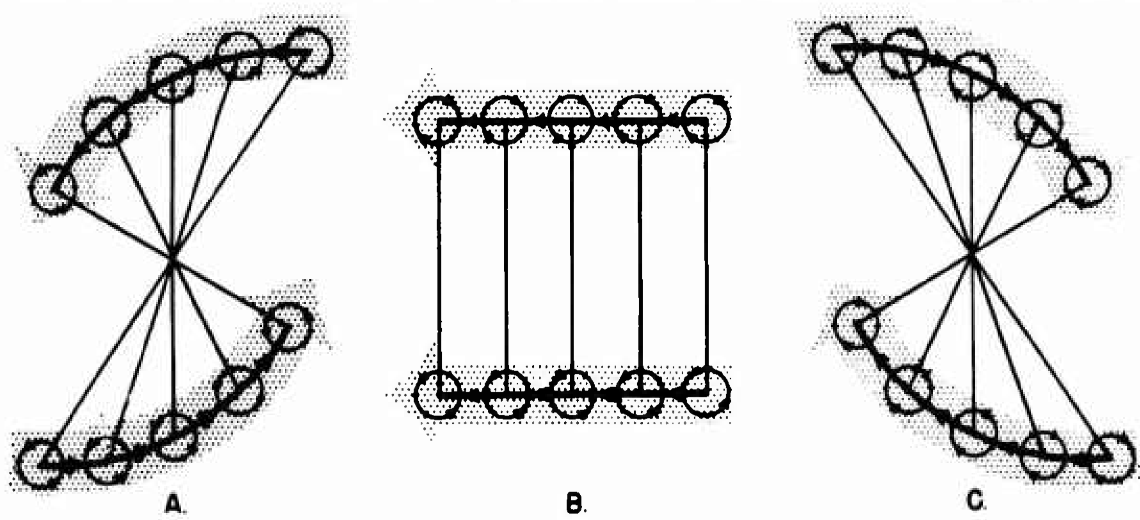
In many problems of hydrodynamics, a two-dimensional field of motion can be treated as if the vorticity were not distributed all over the field, but was concentrated at points, which we will identify as the cyclonic and anticyclonic singular points. In this type of problem, the speed and direction of the wind at any place outside the singular points can be attributed to "sources" of vorticity (the singular points) having various strengths, positive (cyclonic in the Northern Hemisphere) and negative (anticyclonic). Hence, the speed and direction of any particle in the field will depend upon its distance from all the point-sources in the field and upon their relative strength. It can be shown theoretically that the point-sources themselves will be in relative motion, as if each exerted a force upon all the others; to find the movement of any source, then, one has to compute the theoretical wind at the point in question, which is due to the presence of all the other point-sources. This imaginary wind is known as the "steering" wind at the point.

Many forecasters unconsciously use this type of reasoning in track prognosis. For example, they attribute a "steering" force of great magnitude to a nearby, intense anticyclone, on the equatorward side of which a typhoon or cyclone is moving. At the same time, they watch the movement and changes of intensity of other cyclones and anticyclones to estimate their "effects" on the typhoon. If the typhoon lies in the trough between two anticyclones, the problem is often the difficult one of determining whether the eastern or the western anticyclonic cell will intensify rapidly during the forecast period; if the former takes place, the forecaster will probably predict continued recurvature, if the latter, he will expect the storm to return to lower latitudes and continue on its westward track.

It cannot be too strongly emphasized that these notions, which are well established in the art, are qualitative and do not imply that the processes described actually occur in the atmosphere. Cyclones do not exert forces upon one another, as do conductors carrying electric current. There is no such entity in nature as a "steering" wind. The ideas are merely convenient tools for dealing with a very complex practical and theoretical problem. As long as this is understood, there is no objection to considering the singular points as if they were sources of vorticity, exerting forces upon one another and upon the intermediate fields of motion.

7611. Steering. The concept of a cyclone being steered by a broad current in which it is imbedded appears to work well, as long as the cyclone remains small and remains in a deep, broad current. By the time a tropical cyclone has reached hurricane intensity, these conditions seldom exist. It then becomes necessary to integrate the winds at all levels through which the cyclone extends and in all quadrants of the storm, to determine the effective steering current. If sufficient data were available for this type of computation, it might then be possible to obtain the instantaneous direction and rate of movement of the cyclone. However, the mean movement for any given period can be determined more easily with only two accurate fixes on the center. In either case, the future movement of the storm must be predicted mainly upon the basis of extrapolation. The steering principle does have practical applications, however. For example, changes in the winds at one or more levels in the area surrounding the cyclone can sometimes be anticipated, and in such cases, a qualitative estimate of the resulting change in the movement of the cyclone can be made. Conversely, when it appears likely that none of the winds in the vicinity of the cyclone will change appreciably during the forecast period, no change in the direction and speed of movement should be forecast.

7612. The Fujiwhara Effect. Another concept, based on the analogy described in Section 7610, which has certain practical applications, is that known as the Fujiwhara effect. A cyclone tends to make other vortices rotate



7-10. *The interactions of rotating fields in a fluid; (A) cyclone pair, (B) cyclone and anticyclone, (C) anticyclone pair. These examples refer to the Northern Hemisphere.*

about it in a cyclonic direction, and an anticyclone tends to make them rotate about its periphery in an anticyclonic direction. In the same hemisphere, cyclone pairs tend to rotate cyclonically, relative to each other, and anticyclone pairs tend to travel around each other anticyclonically, as shown in figure 7-10. Neighboring cyclones and anticyclones exert a "force" upon each other which is directed parallel to the wind flow between them. Of course, when the two rotational fields lie in opposite hemispheres, the clockwise or counterclockwise direction of rotation is considered, regardless of whether it is called cyclonic or anticyclonic. Thus, two cyclones lying near each other, one on either side of the equator, exert a force on each other toward the east. Usually this effect is much smaller than that of the poleward anticyclones and appears only as a retardation of the normal westward movement. The apparent effect of one rotational field upon any other varies directly with its size and rate of rotation and inversely with the distance between the two centers.

Quantitative methods of applying this concept to the movement of tropical cyclones have not been found. However, it can be used qualitatively. For example, as two cyclones draw closer together, each will be deflected more and more by the cyclonic rotation of the other; the smaller and weaker of the two will be deflected the greater amount. As a cyclone intensifies, to become a typhoon or hurricane, smaller vortices in the vicinity are forced to travel around it at an increasing rate. Many apparently erratic cyclone tracks can be explained when it is seen that the cyclone passed from the influence of one large anticyclone to that of another. Very large typhoons are often seen to overcome the effect of nearby anticyclones and travel in a line, almost straight, for many hundreds of miles, without recurving poleward.These were called "super typhoons" by Ramage (1954). They sometimes exert enough force to cause a small anticyclone to move westward with them; at least this is what appears to happen on the map.

7620. Forecasting the Track.

One of the fundamental problems of forecasting the movement of tropical cyclones is that of recurvature, i.e., will the cyclone move along a relatively straight line until it dissipates, or will it follow a track which curves poleward and eastward?

When recurvature is expected, the forecaster must next decide where and when it will take place. Then, he is faced with the problem of forecasting the radius of the curved track. Even after the cyclone has begun to recurve, there are a great variety of paths that it may take. At any point, it may change course sharply to the west or southwest, or, after moving up to the subtropical ridge line, it may loop back to the southwest. Fortunately, the cyclone usually moves very slowly during these changes in course.

7621. Extrapolation. At present, the most practical prognostic technique used by the tropical meteorologist consists of extrapolating the past movement of the synoptic features on his chart into the future. The past track of a cyclone represents the integrated effects of the steering forces acting upon it. Accelerations and changes in course are the results of the changes in these "steering forces". The effect of these forces can be examined and extrapolated directly from the past positions of the cyclone.

Before applying the extrapolation technique, the forecaster must attempt to smooth out the minor irregularities in the past track. The cyclonic center often oscillates about a smooth track in a wavelike manner, and slight errors in past positions produce other irregularities. The first step in the use of extrapolation is to determine the mean direction and speed of the cyclonic center between each two known positions. The next step is to determine the rate of change in direction and speed between successive pairs of fixes. One convenient method of examining these changes is to determine the westward component and the northward component of the storm track between each two positions, and plot each of these on graph paper, with time as one coordinate.

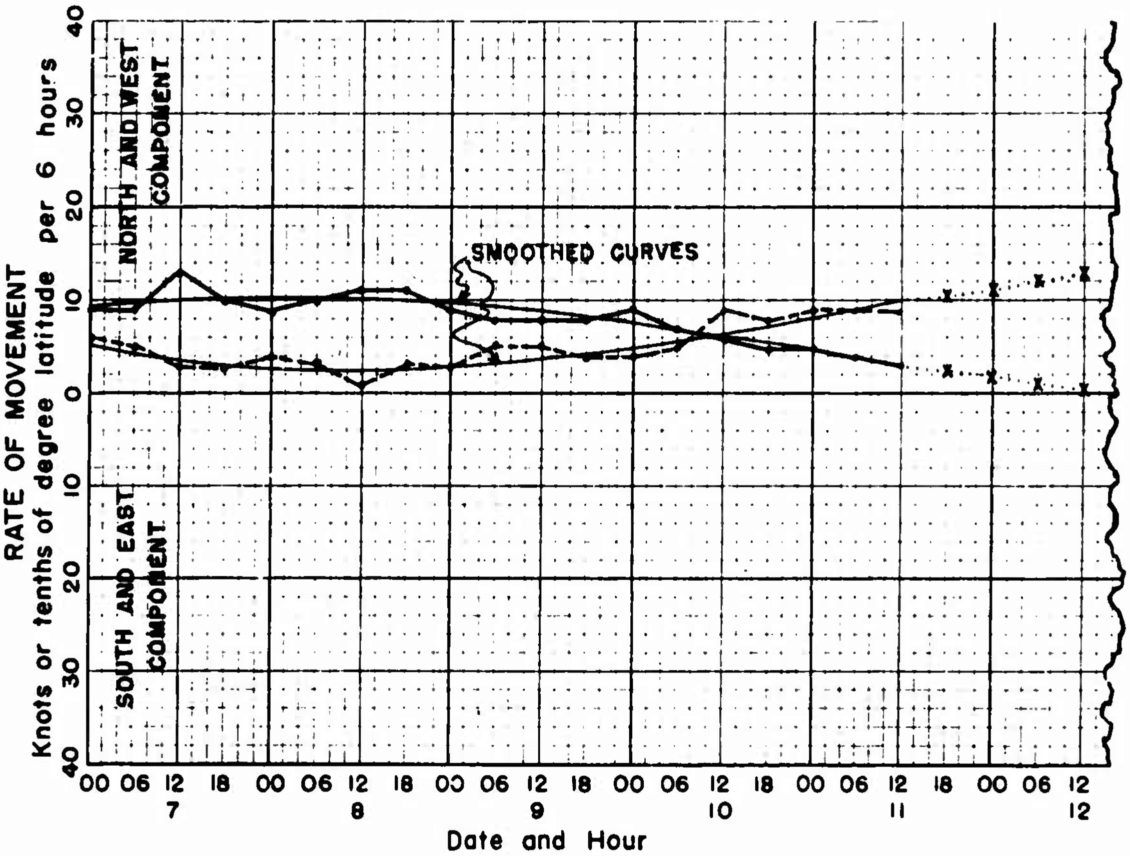


Fig. 7-11. A graph of the westward (———) and northward (– – – –) components of a cyclone track. The extrapolated curves (··········) indicate a forecast of the 24-hour movement of .7° (42 nautical miles) to the west and 4.6° (276 nautical miles) toward the north.

Each of the plotted curves can then be extrapolated separately to obtain a forecast of the future movement, as shown in figure 7-11. This forecast should then be modified, conservatively, to conform with expected changes in the steering effects. The modified forecast should then be compared to the applicable climatological tracks of cyclones in the area and, when a large difference exists, a complete re-examination of the forecast should be made.

A well known method for quickly computing the past speed of movement of any synoptic feature on a weather chart is simply to measure the movement for six hours, in tenths of degrees of latitude, to obtain the speed in knots.

7622. Recurvature Rules. Numerous rules for forecasting the recurvature of tropical storms have been proposed by both theorists and practicing forecasters. All of these rules appear to center around variations in the position, strength and vertical slope of the major subtropical anticyclones and the neutral points between them, relative to the cyclone. These large anticyclones normally slope equatorward and westward with height. Thus, a vertical cyclone located south of the anticyclonic belt must lie much closer to the ridge line aloft than it does at the surface. The upper limits of the cyclone may lie in, or even poleward of, the anticyclonic ridge line at those levels and thus may be influenced by the northward, southward or eastward components of the anticyclonic circulations at those levels. The resulting steering effect of these components is roughly proportional to the pressure thickness of the portion of the cyclone on which they act.

The strongest northward and southward components, in an anticyclone, lie in the area near the east-west line between the singular point at the anticyclonic center and its outer limits. When anticyclones are arranged in a band, as in the subtropical ridge, the outer limits of each circulation are marked by the neutral points between the anticyclones. These neutral points also mark the equatorward limits of the westerly troughs at any given level. Thus, a cyclone approaching a westerly trough from the east may, at some upper levels, come under the influence of the strongest southerly flow around an anticyclone. When this southerly flow is sufficiently strong and acts upon a thick enough layer of the cyclone, the latter will be deflected poleward. If the cyclone remains under the influence of the same anticyclone long, recurvature will be completed and the cyclone will pass into higher latitudes. If, however, the anticyclones are moving eastward, the cyclone may come under the influence of the northerly winds on the forward side of the succeeding anticyclone and be deflected back toward the equator.

To make a qualitative estimate of these effects, it is necessary to have an accurate analysis of the winds, indicating the positions of the anticyclones and neutral points at all levels through which the cyclone extends. Their movements must be forecast before their effects on the future track of the cyclone can be evaluated.

The following criteria for evaluating the steering effect of the major anticyclones have been determined empirically and appear to be valuable guides to the forecaster:

(1) When the neutral point at the southern extremity of the trough in the westerlies, at the 20,000 foot level, lies at or equatorward of the latitude of the cyclone, recurvature into the trough will usually occur. In this situation, the cyclone would normally be under the influence of southerly winds from its upper limits to a level well below 20,000 feet, while approaching the trough.

(2) When the subtropical ridge at 20,000 feet is narrow and broken into many small cells recurvature is unlikely. When it is broad and consists of large anticyclones recurvature will usually occur. The first case represents a high-index situation in which the anticyclones are weak and move rapidly eastward, thus exerting little influence on the cyclone. The latter case represents a low index situation in which the cyclone remains under the influence of a single, large, slow-moving anticyclone for a relatively long time.

Upper level cyclones are also known to influence the tracks of tropical cyclones; in fact, many of the more complex tracks appear to have resulted from the forces exerted by upper level cyclones. No empirical rules for evaluating their effects upon the tracks of low level cyclones have been developed, however.

7700. OROGRAPHIC EFFECTS.

Upon crossing a coast and moving inland, tropical storms and hurricanes usually dissipate rapidly. Just how rapidly depends upon the height of the terrain, the dryness of the surface and the humidity of the air masses encountered over the land. Even mountainous islands have been known to destroy small intense storms completely.

The largest hurricanes and typhoons seldom retain their identity after moving far inland over mountainous regions. They do, however, rétain their identity as they move many hundreds of miles inland along broad river valleys, such as the Ganges in Northern India and the Mississippi in the United States. They also appear to dissipate more slowly when there have been previous heavy rains over the area into which they are advancing. Even in passing over narrow peninsulas they seem to have an affinity for low areas and mountain passes. Cyclones which move out to sea again, after crossing a land area, usually regenerate rapidly. Even storms which appeared to have been almost completely destroyed over land have been known to acquire hurricane intensity once again.

There are accounts of storm centers decelerating over land to the extent that the pressure minimum moved ahead of the calm eye. These accounts may be based on cases where the cyclone filled so rapidly that the lowest pressure at points along the track occurred before the passage of the center. This illusion could be created if the position of the pressure center were based upon the time of passage of the minimum pressure at points along the track rather than upon synoptic charts on which the center of the vortex and the low pressure center were identified at different locations.

7800. THE STATE OF THE SEA.

Although hurricane winds are often directly responsible for great destruction, most of the major hurricane disasters of history have been due to inundations of populated areas, caused by the effects of these winds upon the sea.

The evaluation and prediction of the state of the sea in the area influenced by a tropical cyclone require the skills of an oceanographer. However in the absence of an oceanographer, the meteorologist is often expected to have mystic powers which will enable him to predict the dimensions and effects of waves, swells and tides. This section is designed to acquaint the forecaster briefly with the problems involved and the techniques which may be used in solving them.

Wind has two primary effects on the surface of the sea. First, it creates shallow currents in the surface water and, second, it creates waves on the sea surface.

7810. The Storm Tide

The wind driven currents are oriented roughly parallel to and move in the direction of the surface winds. The strength and depth of the current are determined largely by the strength and steadiness of the wind but are difficult or impossible to evaluate on the basis of wind data alone. Winds in the right half of a tropical storm, relative to its line of motion, are generally very strong and often blow from a relatively constant direction over a very large area. These winds tend to establish a current in the sea surface, on the right side of the storm, which moves in the same direction as the storm itself. When the storm moves in a relatively straight line huge amounts of water are pushed ahead of it. These currents have little affect on small isolated islands or the steep coasts of unclosed bodies of water. However, in partially enclosed seas, such as the Bay of Bengal and the Gulf of Mexico, especially where gently sloping coasts exist around these bodies of water, the wind-driven currents pile water onto the beaches. This piling-up, sometimes called the "Storm Tide", often raises the water level 3 to 10 feet near the center of a storm. Its greatest effect is generally felt to the right of the point where the cyclone crosses the coast, near the time of crossing. Storm tides are independent of the normal gravitational tides, and it is therefore possible for both to reach maximum height on a particular shore at the same time.

The height of the storm tide must be forecast mainly on knowledge of the relative strength of the storm, the expected storm track and past occurrances at each place. The primary point is that, in areas where storm tides occur, the danger is greatest when the cyclone center crosses the coast near the time of normal high tide.

7820. Waves and Swells.

Wind blowing over the sea generates waves in the sea surface, which move in the direction of the wind. The waves move out of their source region and decay into swells which continue to move in the direction of the generating wind. The wave height and period is determined by the speed and fetch of the wind. Waves generated by hurricane winds can be tremendous, sometimes over 45 feet in height. In tropical cyclones the largest waves are usually generated in the right rear quadrant of the storm, where the wind is strongest and changes direction most slowly. These huge waves, breaking repeatedly on a shore, can cause tremendous damage.

The theory of wave generation assumes the existence of a fetch over which the wind blows in a constant direction, but in a tropical cyclone the wind direction changes continually. This means that the fetch at any point in the storm circulation must be taken as the distance, upwind, over which the streamlines have little curvature. The streamlines within any 45° sector of the storm, in which there are no major asymptotes, usually conform, within reasonable limits, to this criterion. The speed of the generating wind is taken as the average wind speed along the fetch.

A rough approximation of the wave height and period at any point outside the eye of a stationary tropical cyclone may be obtained by entering the nomogram in figure 7-12, with the fetch and wind speed, and proceeding in the manner illustrated in the example given. In the case of a moving cyclone, the

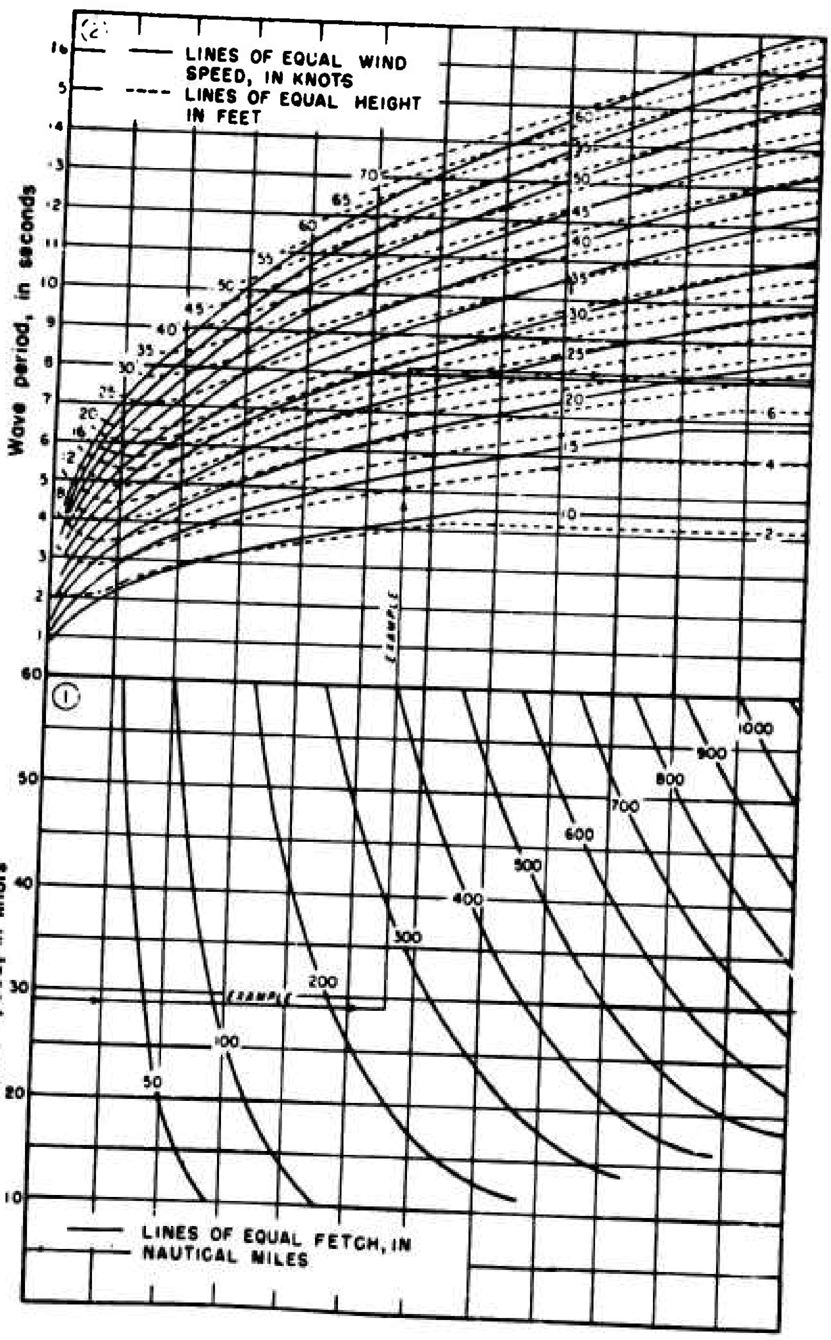


Fig. 7-12. A nomogram for forecasting wave height and period. Example: Fetch 250 nautical miles, average wind speed over the fetch 28 knots, wave height at forward end of fetch 16.7 feet, wave period 8.2 seconds.

fetch of a wave traveling with the storm is lengthened and that of a wave traveling in the opposite direction is shortened. The faster the cyclone moves the greater this effect becomes. The waves themselves accelerate while under the influence of the generating wind, and if the rate of movement of the cyclone increases, it is theoretically possible for waves traveling in the same direction as the storm to have an unlimited fetch. Actually the limit is determined by other factors, such as the cyclone crossing a shore, dissipating, or changing course. Even so, in only two days, a wind of 50 knots, moving always with the speed of the wave, can build the wave to a height of 53 feet. The fact that such development is rare is due to the high rate of movement attained. In the case quoted, the cyclone would have to reach a rate of movement of 22.5 knots while traveling in a straight line.

The wind and wave patterns in a moving typhoon, which passed over a fleet of ships near Japan, are presented in figure 7-13. This storm was moving along a relatively straight, northward course at a speed of 36 knots, near 41° N,

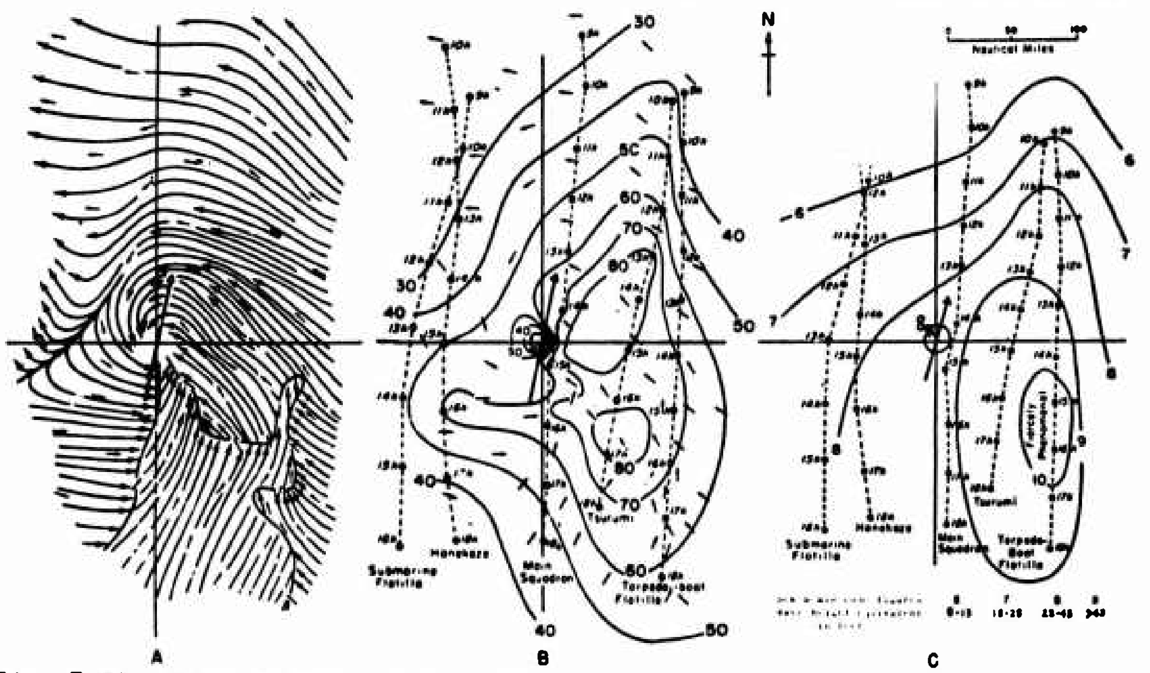


Fig. 7-13. Wind and wave distribution in a Typhoon, A. Surface wind streamlines, B. Surface wind isotachs (knots), C. Wave heights in sea scale units. The arrow through the center indicates the direction of movement of the typhoon. Dots indicate positions of naval units at hourly intervals (JMT). (After Arakawa 1953).

Hurricane swells radiate in all directions from the cyclone. Those from the right rear quadrant usually move in a direction close to that of the storm itself. They generally move faster than the storm center and thus give some warning of its approach. They have a characteristic long period (6 to 15 seconds) and are often detected when breaking on a coast as far as 1,000 miles, or more, in advance of the storm.

When the rate of progression of a storm is increasing, the storm tends to keep up with the swells which are moving along its track. Thus the swells may precede the storm by only a few hours.

7820.

The term "Hurricane Wave" has been applied to the marked rise in the level of the sea near the center of intense tropical cyclones. This rise sometimes amounts to 20 feet or more and affects small isolated islands as readily as continental shores. In partially enclosed seas they may be superimposed on the hurricane and gravitational tides. The hurricane wave may occur as a series of waves but is usually one huge wave. These waves have produced many of the major hurricane disasters of history. There is usually little warning of their approach. However, they should be anticipated near, and to the right of, the center of intense tropical cyclones.

APPENDIX

THEORETICAL AIDS TO ANALYSIS

The branch of mathematics most useful as a theoretical tool in wind analysis is not customarily taught to students of meteorology during their early training. It is called topology, especially the topology of the solutions of certain differential equations. No part of this theory is developed here; however, a few results may be quoted without proof and certain topological features of the isogon field will be pointed out. These topics are not only of interest in themselves but are of practical aid in connection with the analysis of singular points in the wind field.

Owing to the importance of the concepts of divergence and vorticity, as applied to wind fields, and particularly with reference to vertical motions in the atmosphere, knowledge of the relation of these kinematic quantities to the finished analysis can be useful to the analyst. Synoptic meteorologists sometimes use the word convergence or divergence rather loosely to mean that the winds are converging or diverging in direction, and hence that there must be upward or downward motion in the atmosphere in the region showing this convergence or divergence, respectively. This sometimes leads to erroneous conclusions based on a correct analysis and finally to an incorrect forecast. It is essential that the relation between the wind field, the kinematic quantities, divergence and vorticity, and vertical motion be thoroughly understood by tropical forecasters.

It, will be understood in what follows that properties of simple singular points, such as are commonly found on wind maps, are to be discussed. Very complex singular points or singular lines are of such rare occurrence in the tropics that any theoretical investigation of their properties would be irrelevant.

Reference to figures A-2 and A-3 shows that the different singular points are characterized by the appearance of the streamlines in the neighborhood of the zero point. It is possible at a glance, for example, to tell the difference between cyclonic and anticyclonic points. Theoretical study of the differences among the points is facilitated by knowledge of the following theoretical properties:

<u>Property 1</u>: The wind field in the neighborhood of a singular point is sufficiently well approximated, when tangents to the isogons at the point are substituted for the isogons.

Intuitively, this property can be easily seen from figure A-1. The actual isogons on the left-hand side of the diagram enter the singularity at a determinate angle, in spite of the fact that their course at some distance from the point is irregular and curved. The streamlines corresponding to this isogon pattern are given in the diagram immediately below. On the right, straight lines which are tangent to these isogons have been substituted for them, each tangent having the same value as its isogon. The resulting streamline pattern is given below.

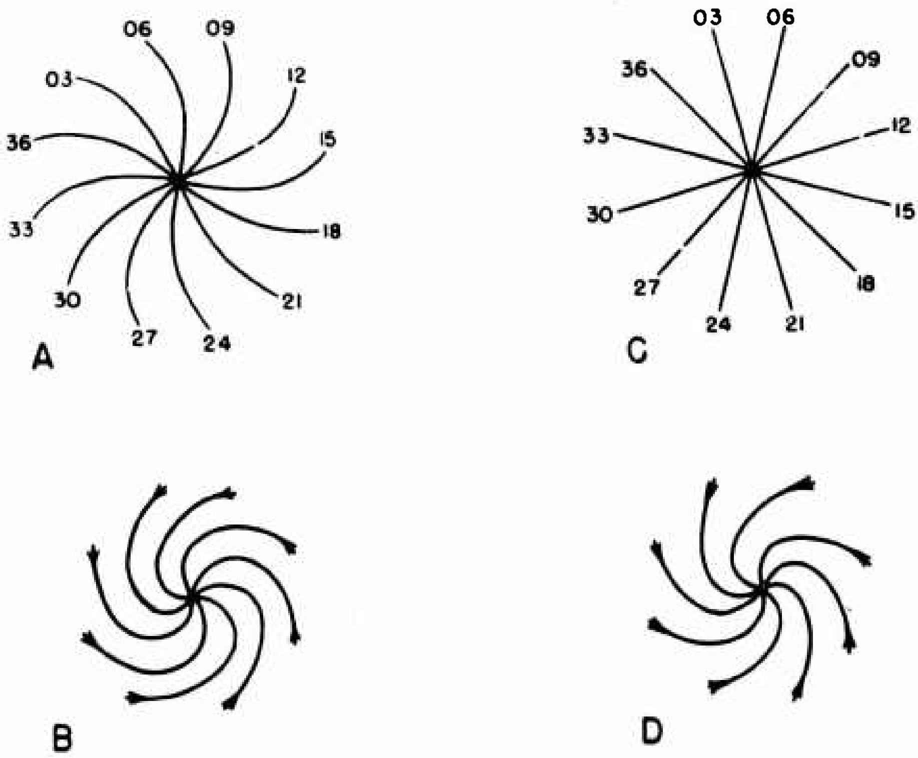


Fig. A-1. Tangents to the isogons, at a singular point, substituted for the isogons themselves. Diagram B is the streamline pattern for Diagram A. "D" is the streamline pattern for "C"

Putting this property in another way, we may say that to study the chief topological features of each singularity it is sufficient to "straighten out" the isogons in the immediate neighborhood of the singularity. This property greatly facilitates the classification of singular points and study of the isogon orientations in their immediate vicinity. Consider figure A-2, for example. A complete set of isogons from 36 through 18, 27, etc., is represented; in diagram A these isogons are straight lines and all directions of the wind are present, although isogons at 30 degree intervals are actually drawn. If a closed curve were drawn around the singular point, not passing through it, and one were to proceed along this curve in a positive direction (counter clockwise) one would cross every isogon. However, the directions, still proceeding in the positive direction, would diminish in value. For example, if one started at the 36, one would then encounter the 33, then the 30, then the 27, etc., each succeeding value of the isogon being less than the preceding. This property is true of every set of isogons represented in figure A-2, the difference between the various points being dependent only upon the orientation of the isogons to the fundamental north-south direction. In diagram A each isogon has the same direction as the wind it represents. Consequently, the isogons themselves are streamlines, all of which diverge from the singularity itself. Such a point is known as an "outdraft". Diagram B resembles the previous one in every particular, save that the whole set of isogons has been rotated through 45 degrees. The order of isogons in the positive direction is the same. The streamline pattern correspond-

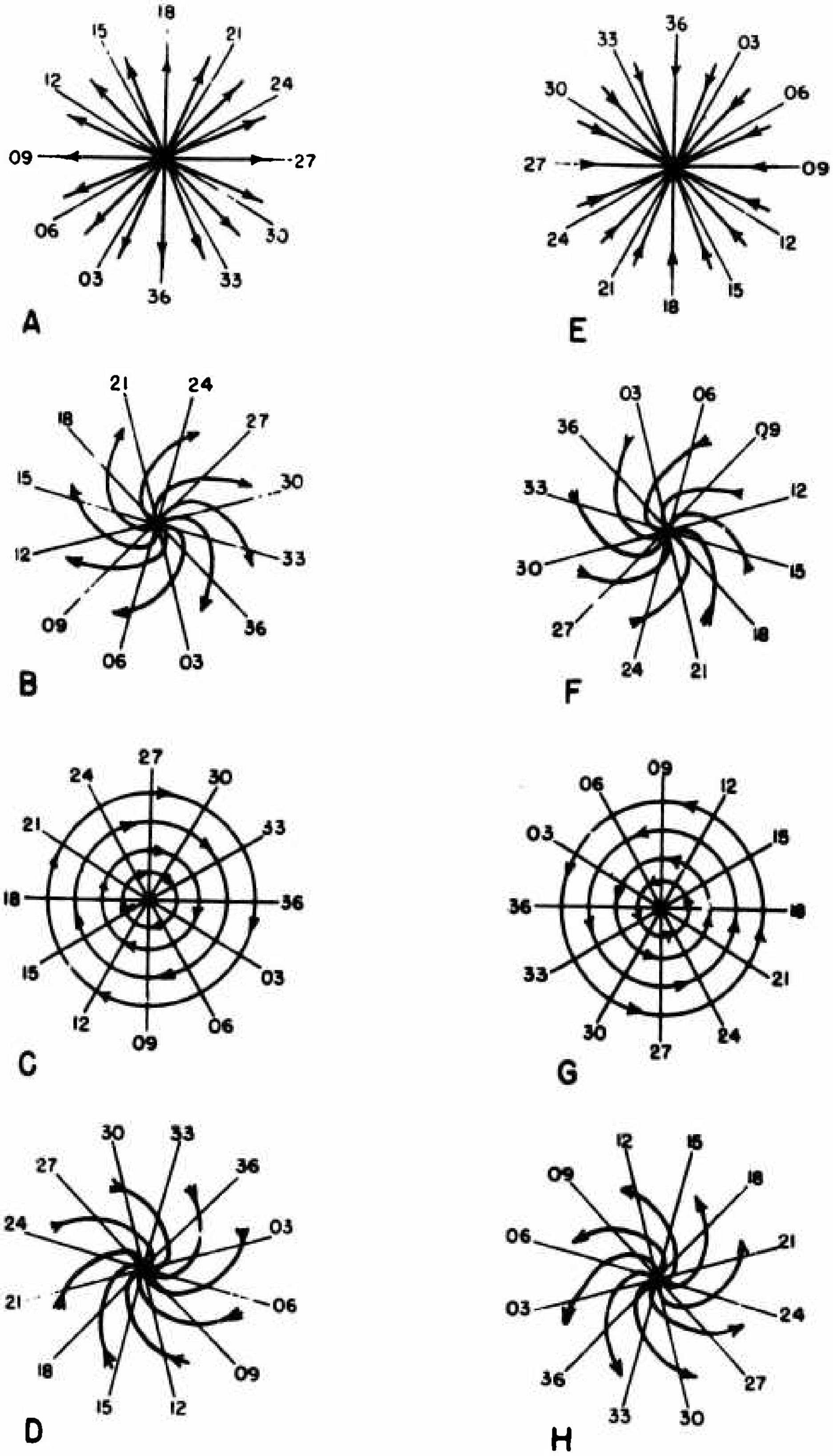


Fig. A-2. Singular points of index plus one, vortices.

ing to this isogon field is also shown. It will be seen that not only do the winds point outwards from the center, but also the whole field possesses rotation. The curvature of each streamline is negative, that is, anticyclonic in the Northern Hemisphere. Such a point is known as an anticyclonic outdraft. Diagram C is formed by rotating the isogons through another 45 degrees. Now the streamlines cut the isogons at right angles, forming a series of closed curves (in this case circles) surrounding the singular point itself. The singular point is "isolated"; no streamline actually joins it. Nevertheless, it is a point of zero wind and hence is to be regarded as a singularity. There is no indraft or outdraft at the point, the streamline field being one of pure rotation in the negative sense. Such a point should be called an anticyclone. Proceeding in this way, that is, by rotating the isogons through 45 degrees, one gets a succession of singularities, all related. The remainder of the diagram is formed in this way. Various patterns are either pure indrafts or outdrafts, pure cyclones or pure anticyclones, or combinations of the first two with the latter two. The cyclonic indraft, for example, is as its name implies, a combination of an indraft and a cyclone. All these patterns, however different they may appear, are closely related; the essential feature being the decrease in isogon value as one proceeds in a positive direction along any closed curve surrounding the singularities.

In figure A-3 we again have a set of isogons which are straight lines. Consider any one of the set formed by successive rotation through 45 degrees. If a curve be described about each point in the positive direction, the values of the isogons increase rather than decrease. As before, successive rotations give different patterns. However, these patterns do not differ qualitatively to the eye like those of the previous figure. They are in fact all hyperbolic or neutral points.

At this point in the discussion it is an advantage to introduce some elementary topological ideas which assist in the classification of different types of singularities. As before, we may surround a singular point and its isogons by a closed curve described in positive direction. In figure A-2 if we describe the curve around any singular point, starting at any point and returning to the same point, we will cross every isogon once. In practical terms, an observer traveling around this curve and holding a wind vane would find that the vane would describe one complete revolution in the positive direction during one passage around the curve. Now we can describe a curve of this kind in any part of the field of motion. The number of revolutions performed by an imaginary wind vane carried in the positive direction around the curve is called the index of the curve. If the vane turns in a counter clockwise direction during this passage, the value of the index is positive. If the vane turns in the clockwise direction, the value is negative. We can immediately state the following property:

> <u>Property 2</u>: The index of a closed curve which encloses no singular points is zero.

This property can easily be verified by drawing any arbitrary wind field not containing a singular point and describing the required curve. It will be found that the vane thus carried around will rotate a portion of the complete circle, either in the positive or negative direction and then rotate in the opposite sense to come back to its starting point. Since only singular points

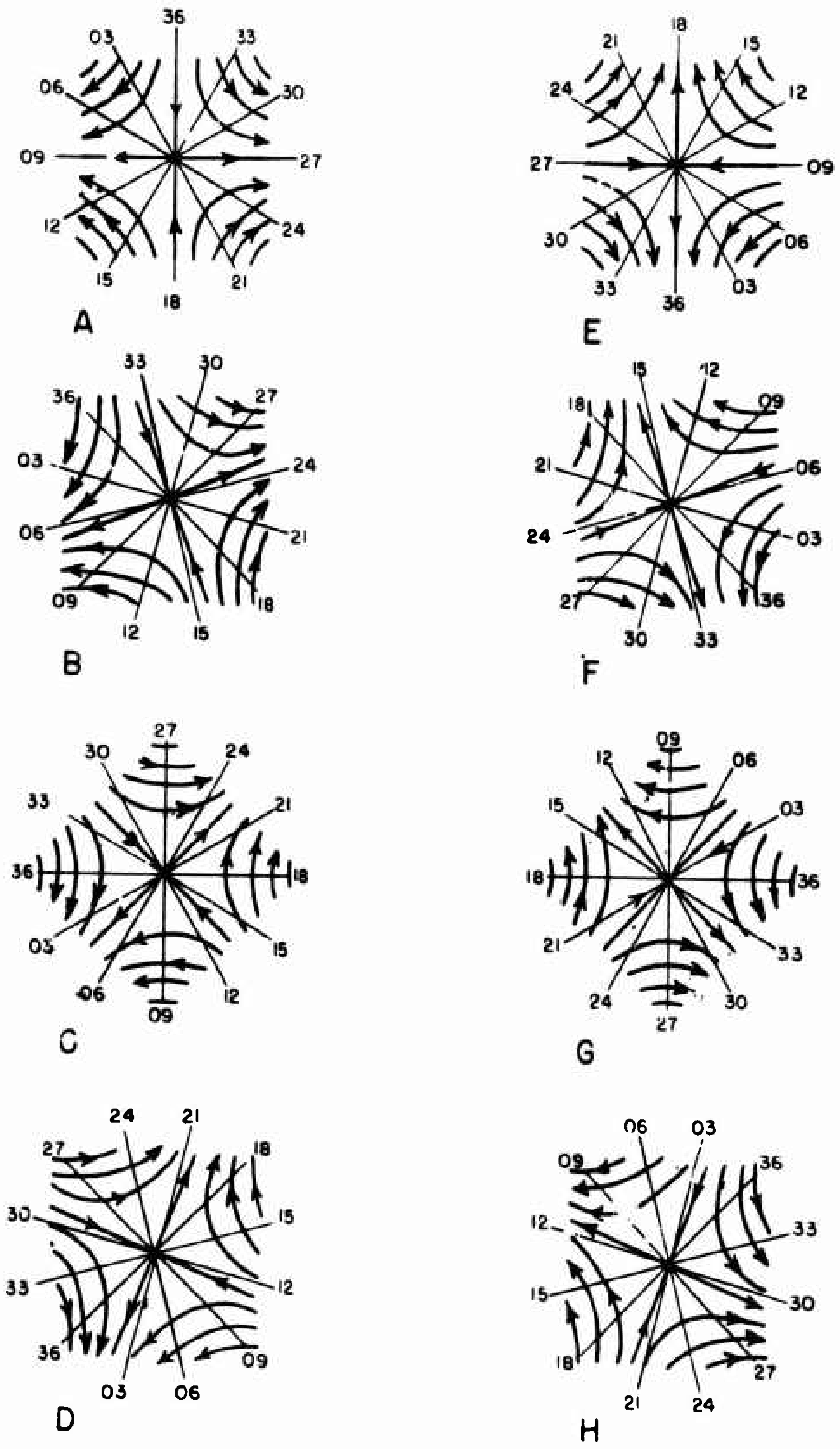


Fig. A-3. Singular points of index minus one, neutral points.

affect the index of the curve, we may without ambiguity, speak of the index of a singular point, it being always understood that the closed curve which is described about the point does not contain it. The reader may easily verify the following property:

<u>Property 3</u>: All the critical points illustrated on figure A-2 have the same index, namely, plus one.

<u>Property 4</u>: All the singular points illustrated on figure A-3 have the index minus one.

The following property can be verified by trial on paper:

<u>Property 5</u>: The index around any closed curve covering any part of the wind field is computed by adding the indices of all singular points lying within it, due regard being taken of the sign.

For example, if a closed curve surrounds both a neutral point and a vortex, the index of the curve is zero.

This suggests that certain singular points may have the value zero -- such is indeed the case. Consider diagram A in figure A-4 where the isogons meet at a singular point; however, if a closed curve is described around this point, in the positive direction, there is not a complete revolution of the imaginary wind vane. If we start at the point marked a, for example, the vane first rotates from 18 to 9 and from 9 to 36. However, after passing 36, the vane does not continue to rotate in the same sense, but returns through the same isogon values to finish at a with 18. There has been a half revolution, first in the positive and then in the negative sense. The index of the singular point is zero. Such a point is known as a cusp point. It is the commonest type of singularity of index zero, both in the easterlies and in the westerlies. However, it is usually short-lived, being a transition pattern during the formation of vortices from waves. As in the case of figure A-2 and figure A-3 we may take the set of isogons representing the cusp point and rotate them in steps of 45 degrees to get a complete set of points of index zero. Figure A-4 illustrates the different patterns obtained by this process. Although the streamlines at A and E bear little resemblance to those at C and G, all have the same index.

The points classified on these diagrams represent practically every kind of simple singularity found on wind maps. More complicated points, of course, are possible. They are illustrated on figure A-5. Diagram A represents a point of index zero which is more complicated than those illustrated in figure A-4. Diagrams B and C represent points of index, plus 2. So far these have not been observed on wind maps though the possibility that they may exist in very turbulent regions remains open. Diagram D represents a point of index minus 2, a complicated neutral point. Such points as these are rarely, if ever, observed on wind maps. They are, however, sometimes seen where there are strong orographical effects, as on the plateaus among the Rocky Mountains. Oceanic analysis containing such points is likely to be in error.

An analyst who intends to carry out isogon analysis seriously will do well to be familiar with these patterns, with the notion of the index and with the possible combinations of two or more points. These theoretical ideas are also useful in the discussion of the synoptic models. Finally, the following property

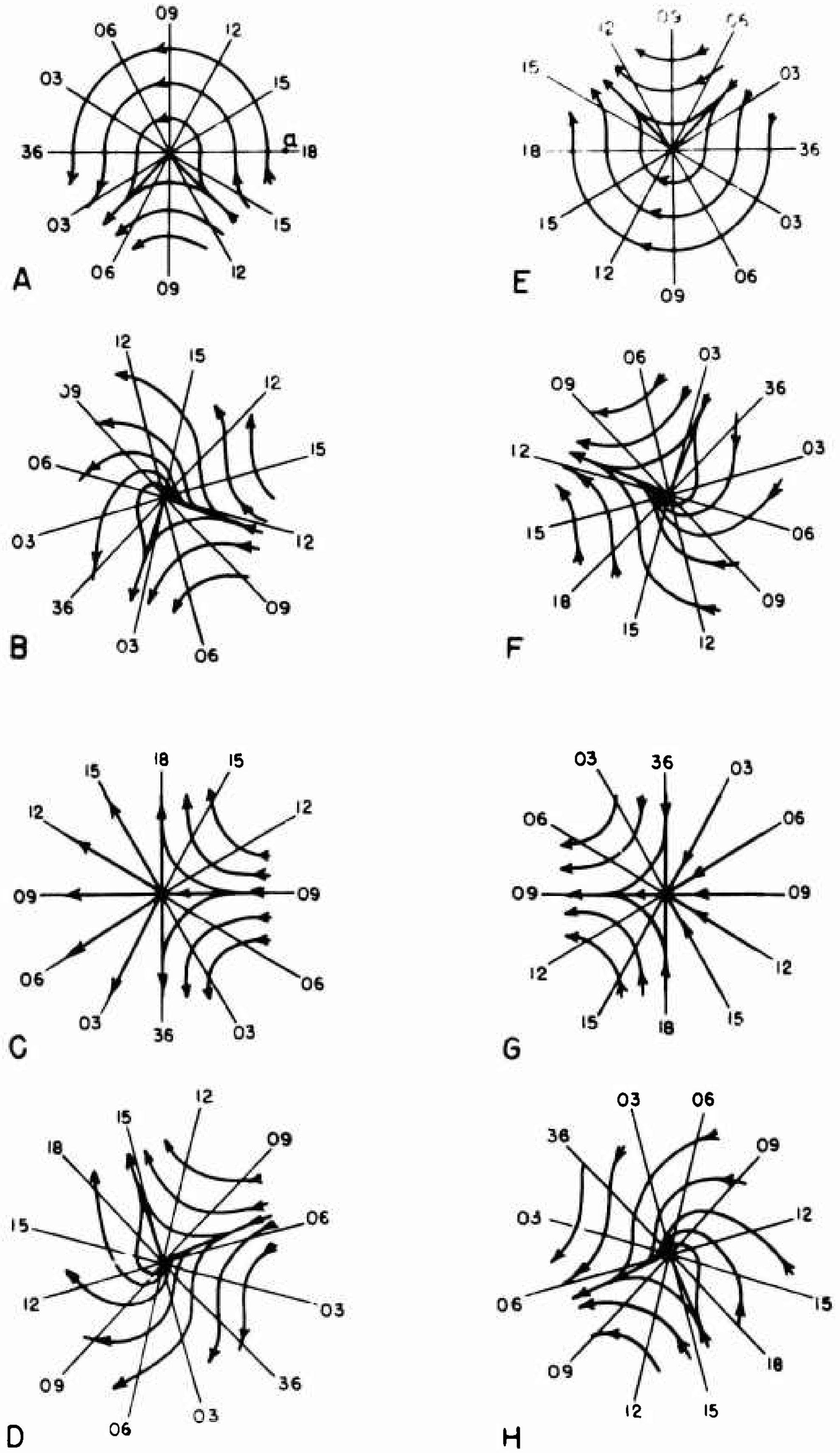


Fig A-4. Singular points of index zero, cusp points.

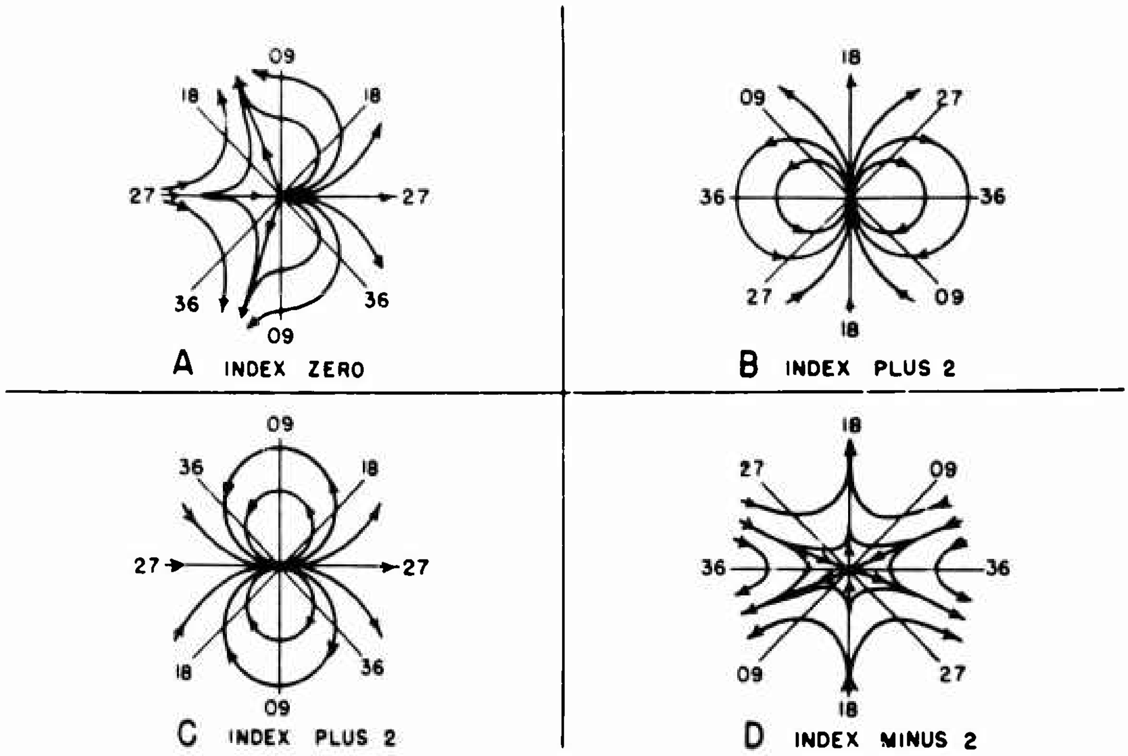


Fig. A-5. Complicated singular points not usually found on wind charts.

may be stated:

> <u>Property 6</u>: On a spherical surface the sum of the indices of all singular points in the wind field is plus two.

For example, the simplest wind pattern which can be drawn on a globe is a straight zonal current circling the globe at all latitudes. When this is done a point of index plus one will be found at each pole. The impossibility of placing another positive point in the field without also drawing a negative point of equal index is obvious, e.g., a neutral point must be added with each vortex. Points of index zero may be added singly. However, the total index always remains plus two.

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4	Final Report on Project 8-52M-1 Tropopause	S. Coroniti	Jul 52	S
5	Infrared as a Means of Identification	N. Oliver J. W. Chamberlain	Jul 52	S
6	Heights of Atomic Bomb Results Relative to Basic Thermal Effects Produced on the Ground	R. M. Chapman G. W. Wares	Jul 52	S-RD
7	Peak Over-Pressure at Ground Zero from High Altitude Bursts	N. A. Haskell	Jul 52	S
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13. ABSTRACT

The report is in seven parts. After a short introduction, the manner in which the tropical forecaster may utilize climatological information is discussed. The next section emphasizes that the approach to the evaluation of tropical data is different from that which is standard in high latitude meteorology. Then follows a long discussion of wind analysis, using streamlines and isotachs. The fifth section covers methods of analyzing cloud and weather distribution; the methods outlined here are designed specifically for use in tropical regions. The sixth section deals with problems of correlation of wind and weather patterns, of continuity and with related topics; the material is presented chiefly in the form of practical examples. Finally, the structure, genesis and movement of tropical cyclones are briefly discussed.

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